



Exchange Bias in Ideal Antiferromagnets

Hongtao Shi
Miyeon Cheon
Zhongyuan Liu
Jorge Espinosa
David Lederman

Hendrik Ohldag
Joachim Stöhr



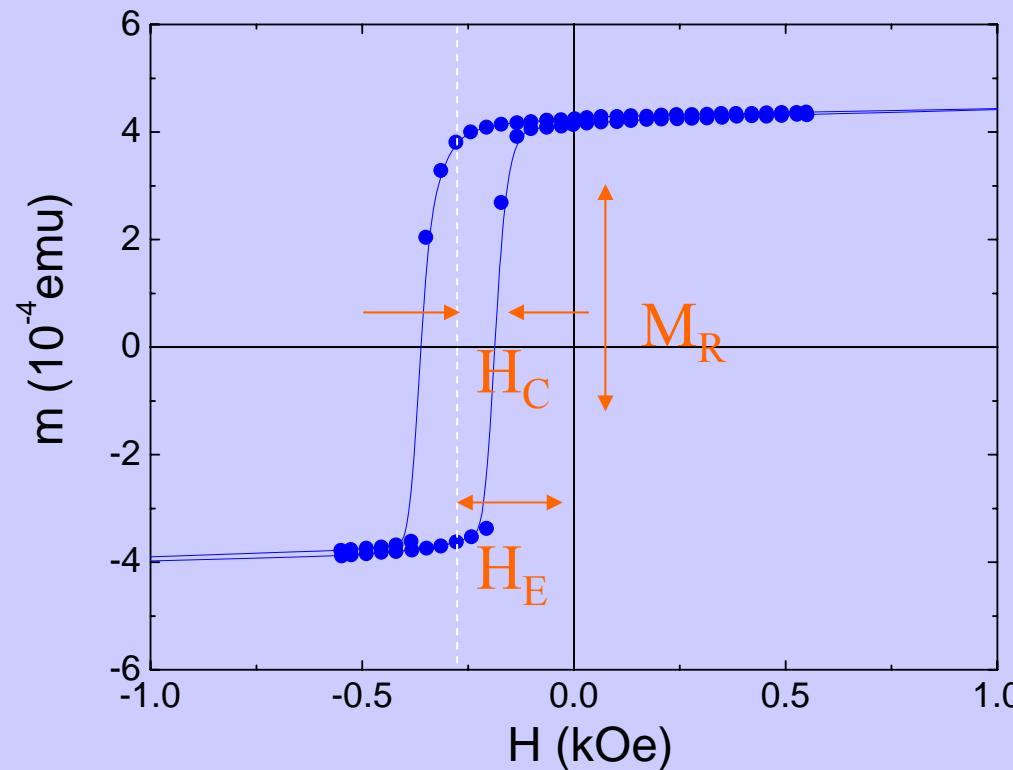
Stanford Synchrotron Radiation Laboratory
A national user facility for academia, industry, and national laboratories

Elke Arenholz





Exchange Bias



M_R : “Remanent” magnetization

- Maximum value of M
- Depends on FM

H_C : Coercivity

- Depends on FM magnetic anisotropy
- Represents energy required to reverse magnetic domain

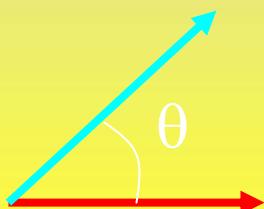
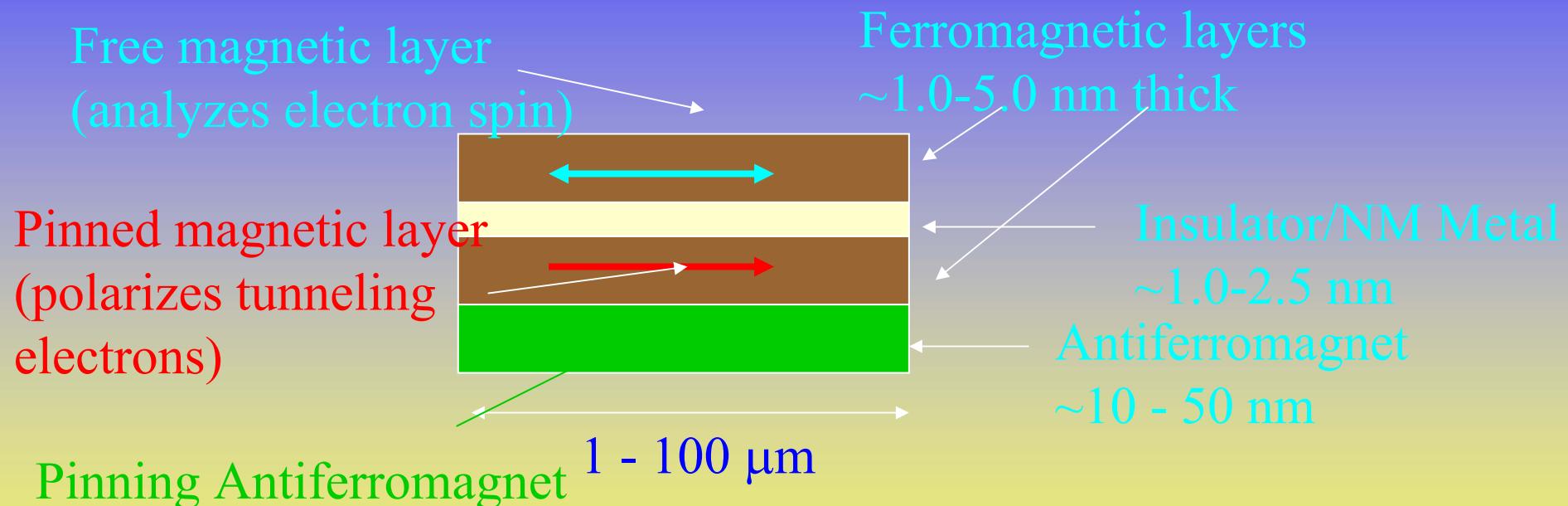
H_E : Exchange Bias

- Absent in pure FM, due to AF-FM interactions





Application: Magnetic Tunnel Junction /GMR Sensors



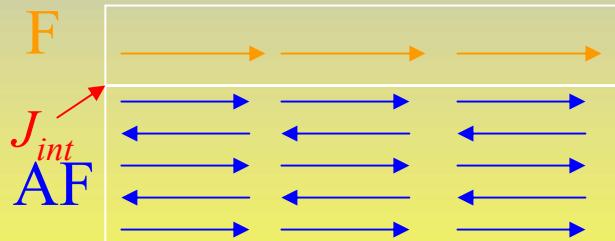
$$R = R_o - \Delta R \cos \theta$$



Direct Exchange Mechanism

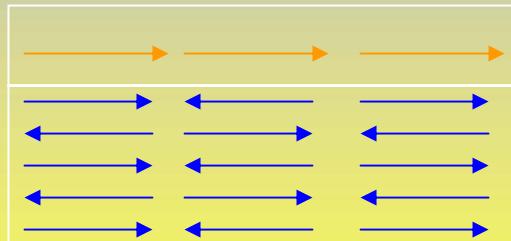
- Direct exchange mechanism (Meiklejohn and Bean, 1956) predicts
 - a) wrong magnitude (~ 100 times too large)
 - b) no exchange bias in compensated or disordered surfaces

$$H_E = J_{\text{int}} / a^2 M_F t_F$$

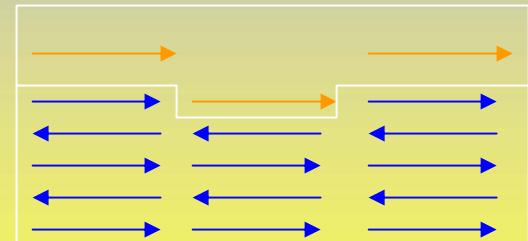


Ideal Uncompensated

$$H_E = 0$$



Compensated



Roughness

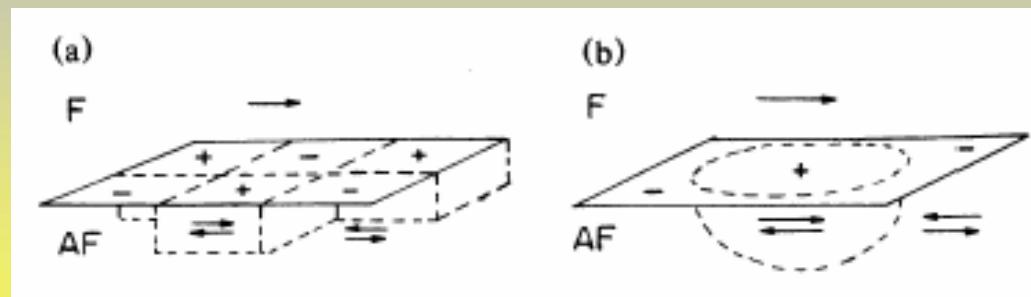


Random Exchange at Interface

- Due to interface roughness, defects, etc.
- Antiferromagnetic domains created with local exchange satisfied during cooling

$$H_E \approx 2J_{\text{int}} / L\pi a M_F t_F$$

L = domain size in AF

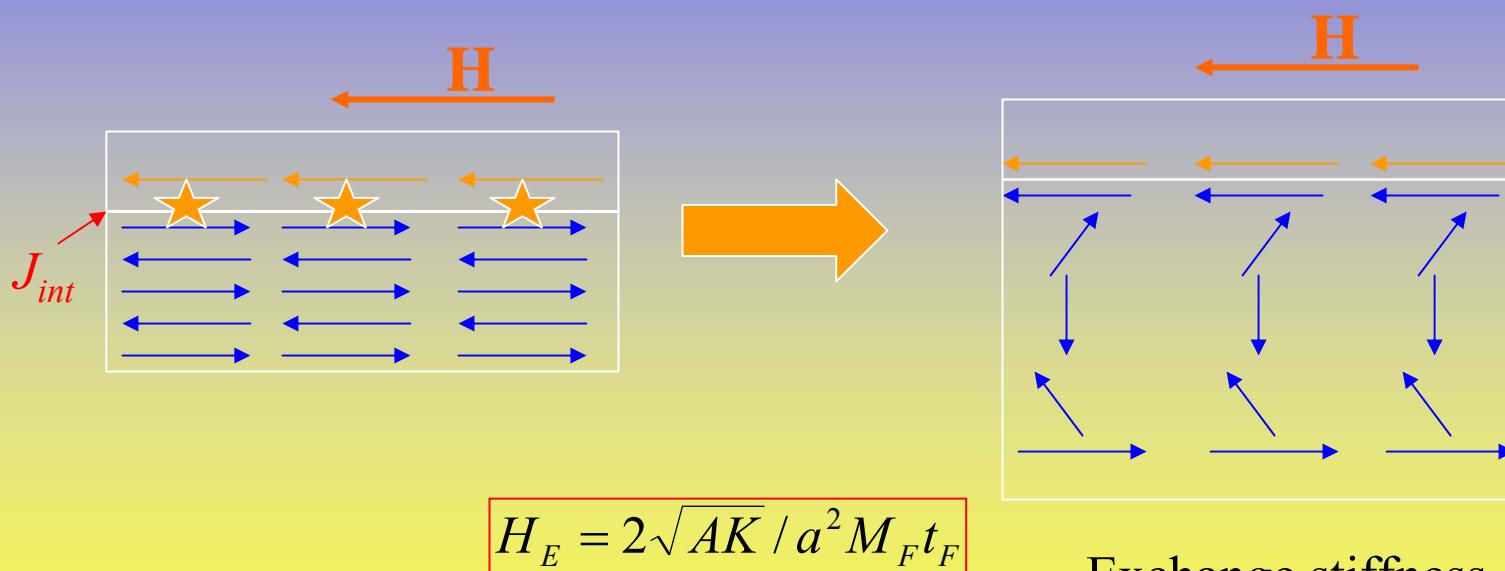


Malozemoff, 1987



AF Domain Wall Formation

- AF or F domain walls created during cool-down procedure



Correct order of magnitude

Exchange stiffness $A = J_{AF,F} / a$
Magnetic anisotropy energy K
Lattice parameter a

Malozemoff, 1987; Mauri et al. 1987



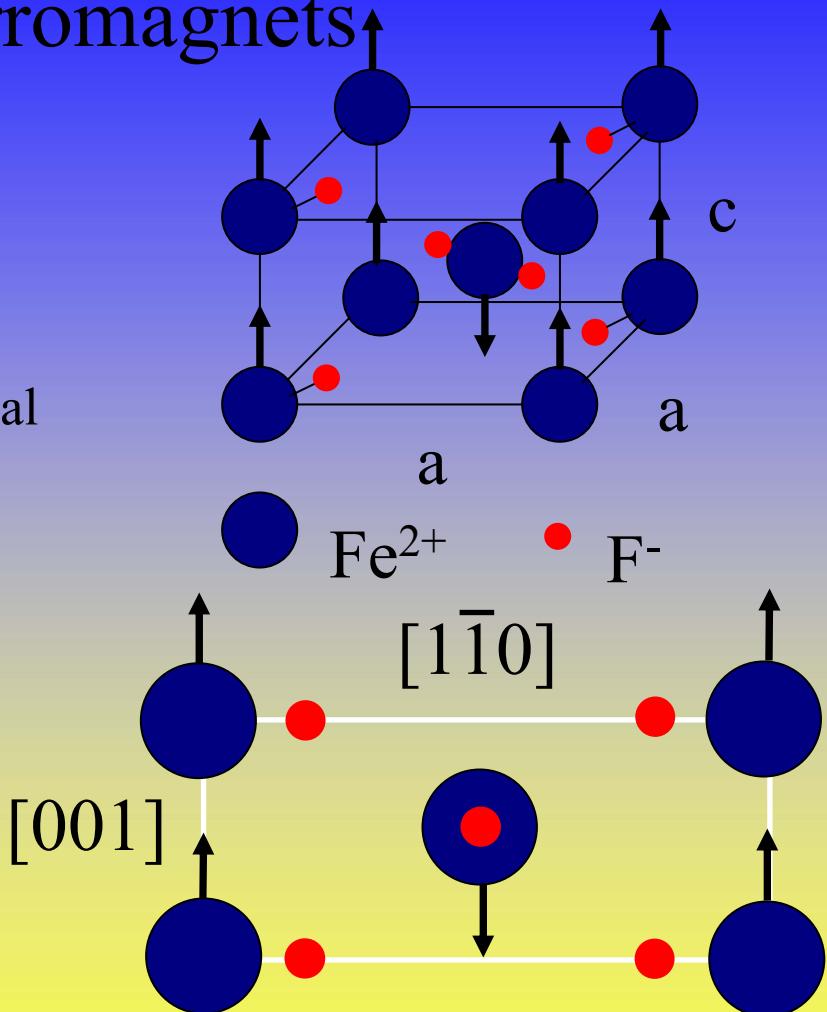
Key Questions

- Given that:
 - All EB models require presence of uncompensated magnetization in the AF
 - Details of EB behavior (e.g. temperature dependence, magnitude) depend strongly on AF anisotropy
- Some key questions are:
 - Can uncompensated moments in the AF be detected?
 - Can the effects of uncompensated moments in the AF be studied systematically?
 - Can the magnetic anisotropy be studied systematically?



MF₂ Antiferromagnets

- FeF₂: Ideal **Antiferromagnet**
 - $T_N = 78.4$ K
 - strong uniaxial magnetic anisotropy along *c*-axis
- Body-centered-tetragonal (bct) crystal structure
 - $a = 0.4703$ nm, $c = 0.3305$ nm
- ZnF₂: **Non-magnetic**, bct crystal
 - $a = 0.4711$ nm, $c = 0.3132$ nm
- MgF₂: **Non-magnetic**, bct crystal
 - $a = 0.4620$ nm, $c = 0.3051$ nm

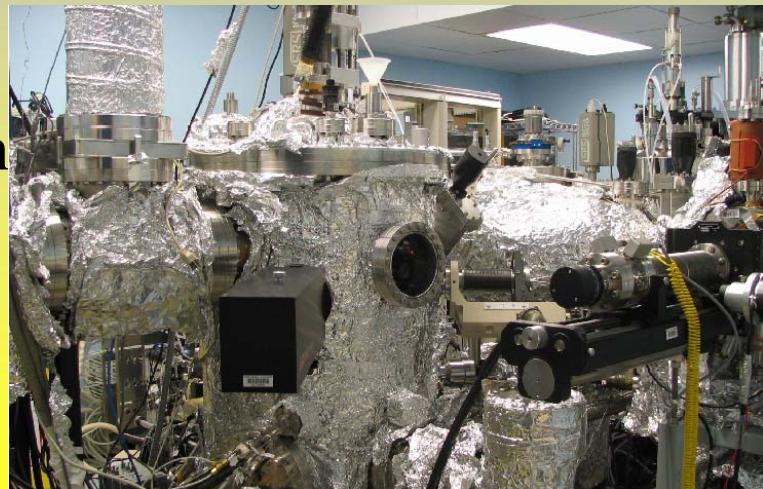


Small lattice mismatch between FeF₂, ZnF₂, NiF₂, and MgF₂



Growth and Characterization

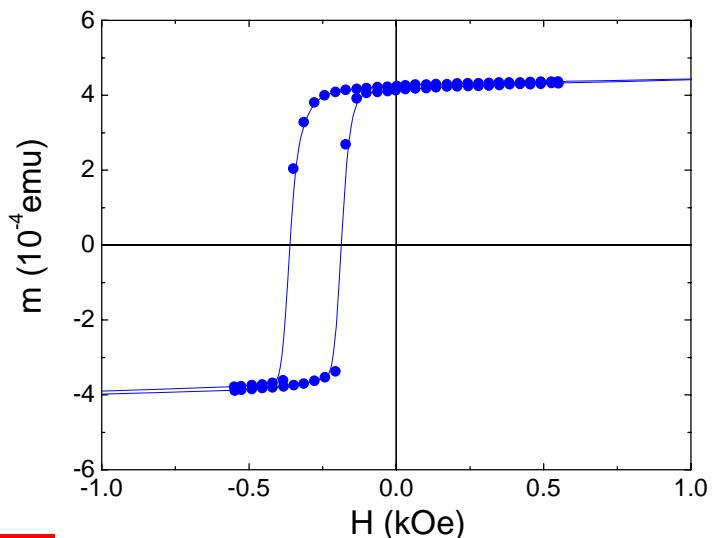
- MBE co-deposition of FeF_2 (e-beam) and ZnF_2 , NiF_2 (K-cell),
 $P_{\text{base}} = 7 \times 10^{-10}$ Torr, $P_{\text{growth}} < 4 \times 10^{-8}$ Torr
- $T_S(\text{AF}) = 297$ °C, poly-Co @125 °C, poly-MgF₂ @RT
- Growth along (110)
- **Twin sample holder – simultaneous growth of underlayer, different overlayers**
- In-situ RHEED, AFM
- X-ray diffraction and reflectivity
- Cooling field ($H_{CF} = 2$ kOe) in the film plane along the *c*-axis of $\text{Fe}_x\text{Zn}_{1-x}\text{F}_2$
- *M* vs *H* via SQUID magnetometer, horizontal sample rotator





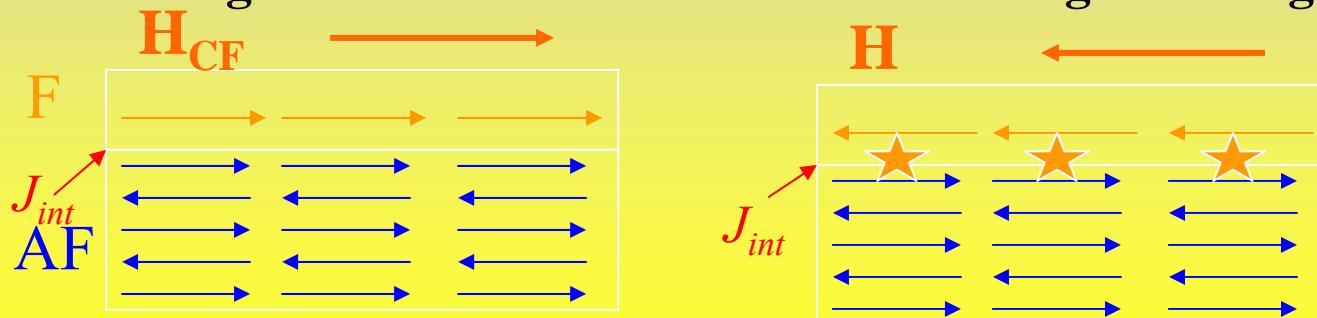
Measurement Procedure

1. Cool in H_{CF} from above $T = T_N$
2. Measure M vs. H at $T < T_N$



Conventional view: $E_{\text{int}} = -J_{\text{int}} \sum S_{i,A} \cdot S_{j,F}$

Interface exchange interaction sets low T antiferromagnet configuration



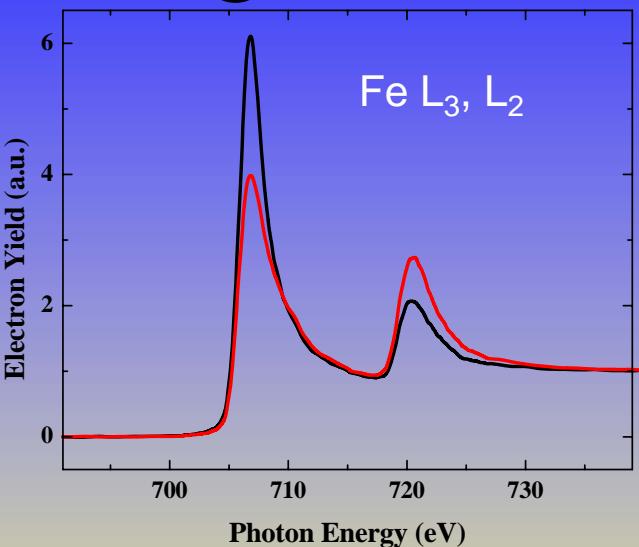


Key Questions

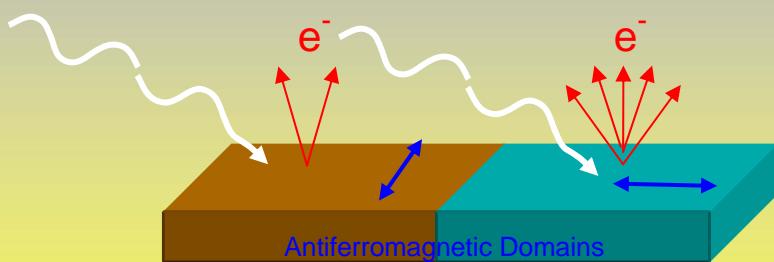
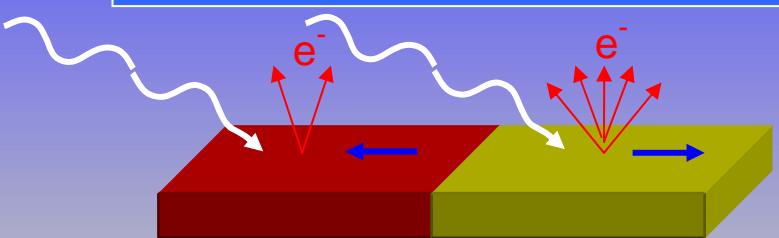
- Can uncompensated moments in the AF be detected?
- Can the effects of uncompensated moments in the AF be studied systematically?
- Can the magnetic anisotropy be studied systematically?



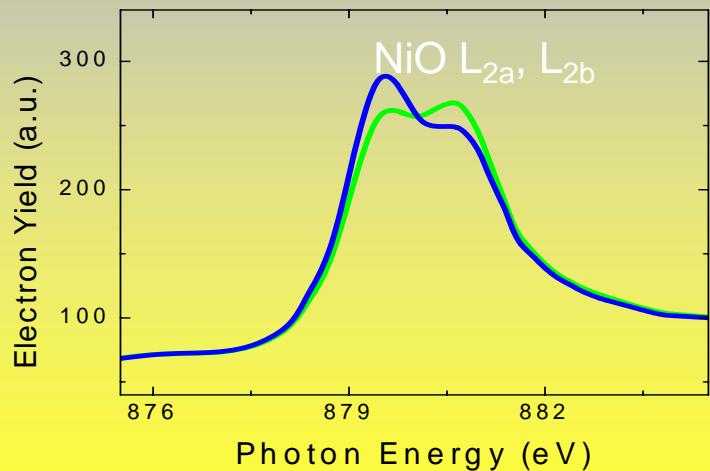
Magnetic Dichroism in X-ray Absorption



X-ray magnetic **circular** dichroism
→ sensitive to FM order.



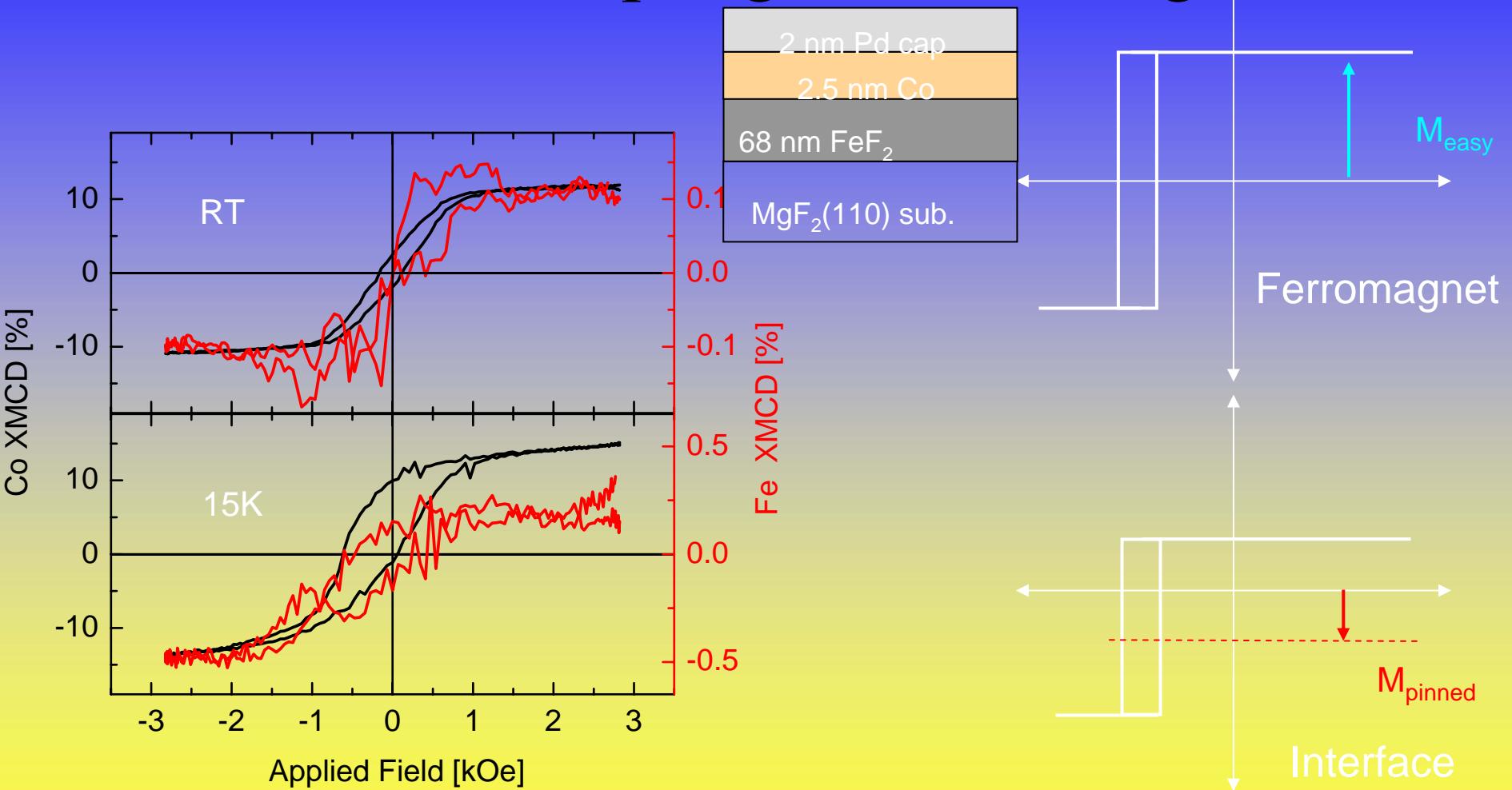
X-ray magnetic **linear** dichroism
→ sensitive to AF order.



Element specific technique sensitive to antiferromagnetic as well as ferromagnetic order.



Interface Coupling and Exchange Bias

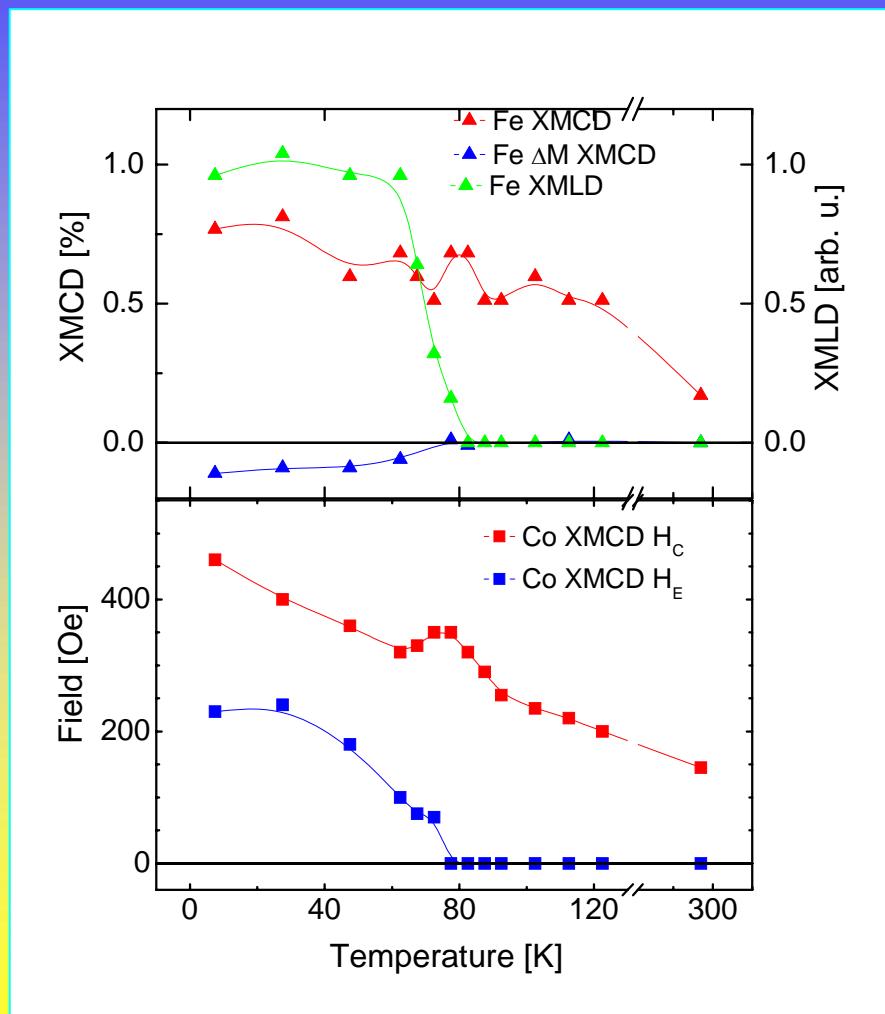


Room T: “Free” uncompensated moments follow FM

Low T: Additional “pinned” uncompensated moments oriented antiparallel to easy direction.



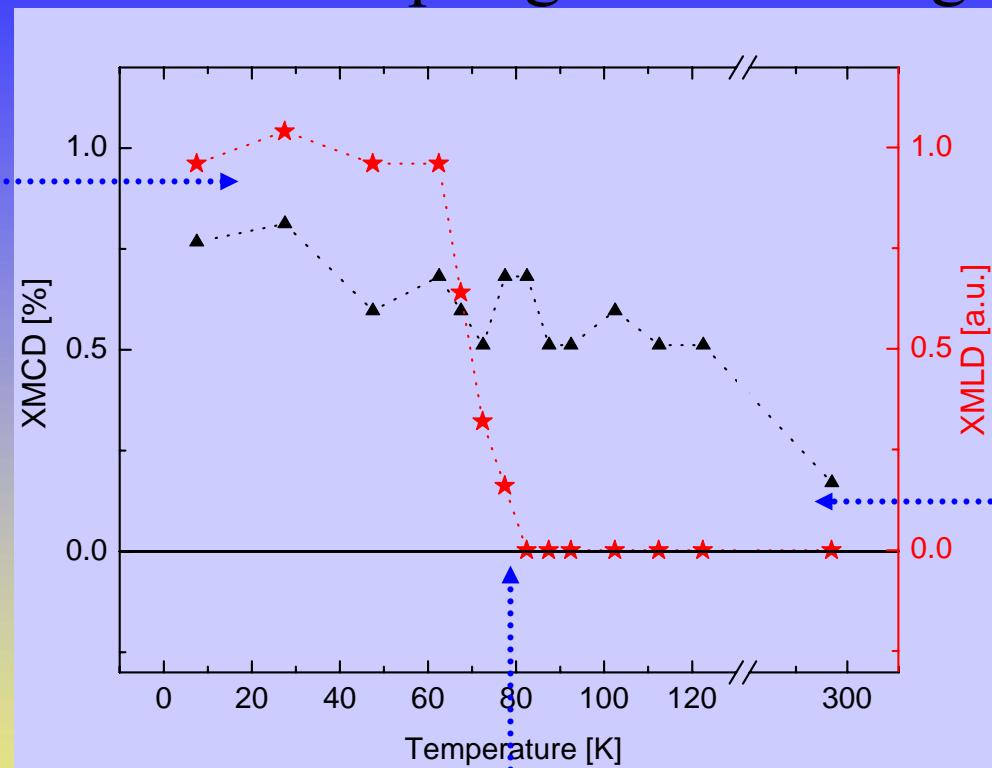
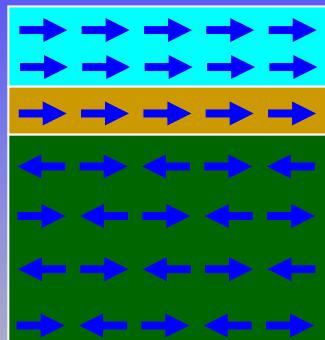
Results



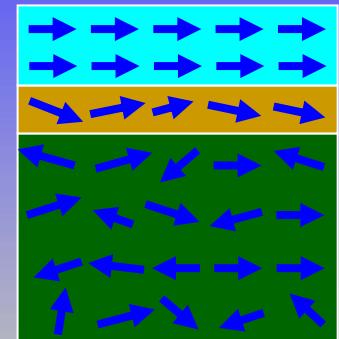
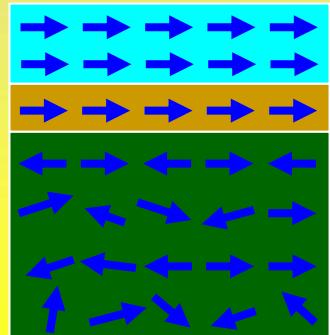
- Iron in FeF_2/Co interface, despite being non-metallic, has
 - Unpinned magnetization to RT
 - Pinned magnetization to T_B
 - AF order verified to T_N via XMLD
- Co at interface
 - $T_B \sim T_N$
 - H_C peak near T_B



Parallel Interface Coupling and Exchange Anisotropy



1.) XMLD and long range AF order vanishes at T_N .



2.) XMCD as indication of interfacial magnetic order at RT.



Related to enhancement of coercivity for $T \gg T_N$
(Grimsditch et al, PRL 2003)

Also, see Roy et al, PRL 2006

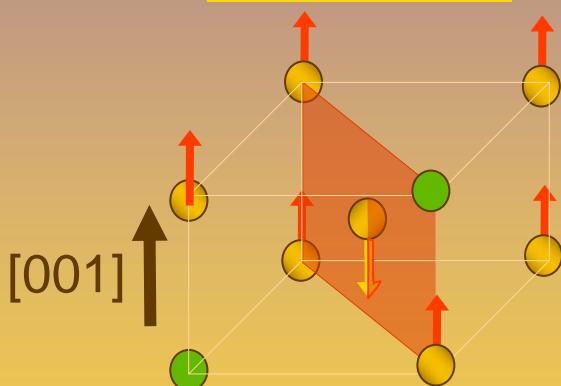


Key Questions

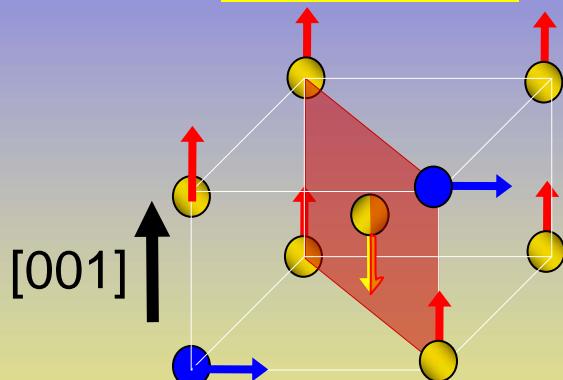
- Can uncompensated moments in the AF be detected?
 - Uncompensated moments exist in AF, not due to “metallization”
 - Can exist up to RT, well above T_N
- Can the effects of uncompensated moments in the AF be studied systematically?
- Can the magnetic anisotropy be studied systematically?



Systems



Dilute antiferromagnet



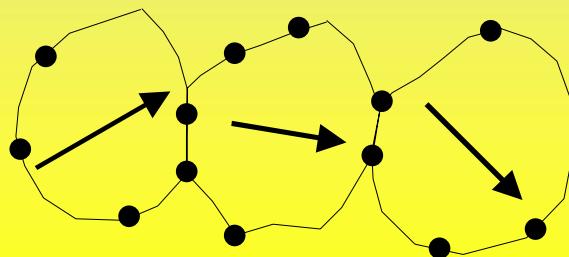
Random anisotropy antiferromagnet

Systematic study of uncompensated M



Effects of Dilution

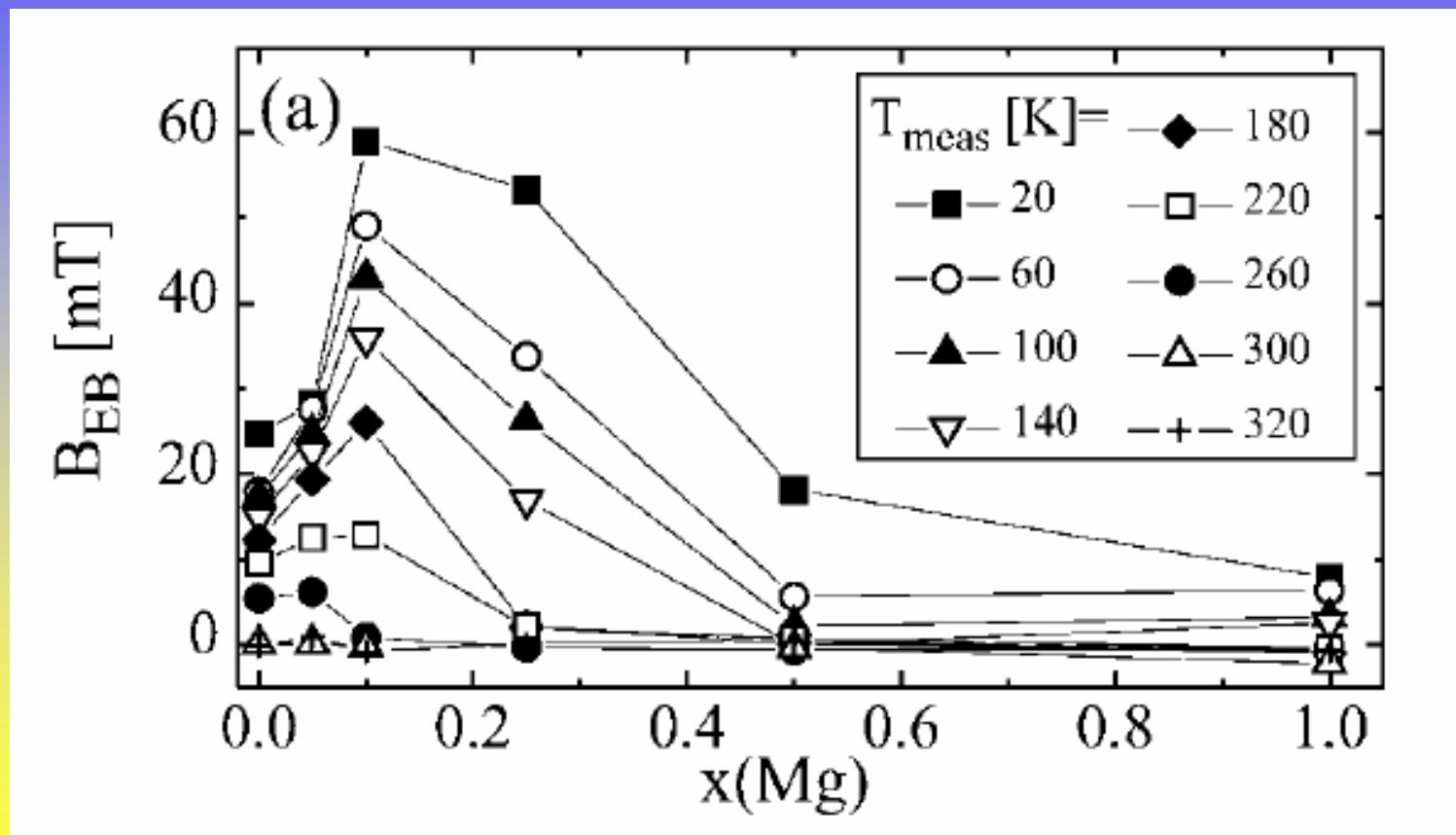
- Domain state model: dilute AF should make small domain creation easier due to nonmagnetic impurities (Malozemoff model)
- Net magnetization of AF domains should increase effective interface interaction





Previous Results

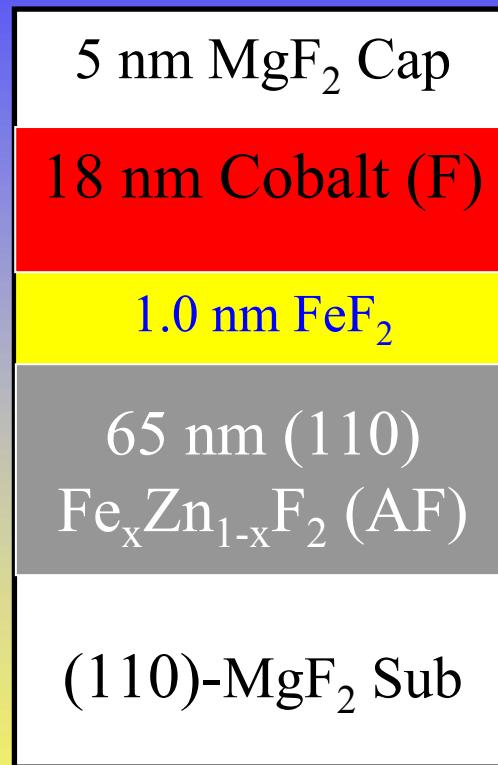
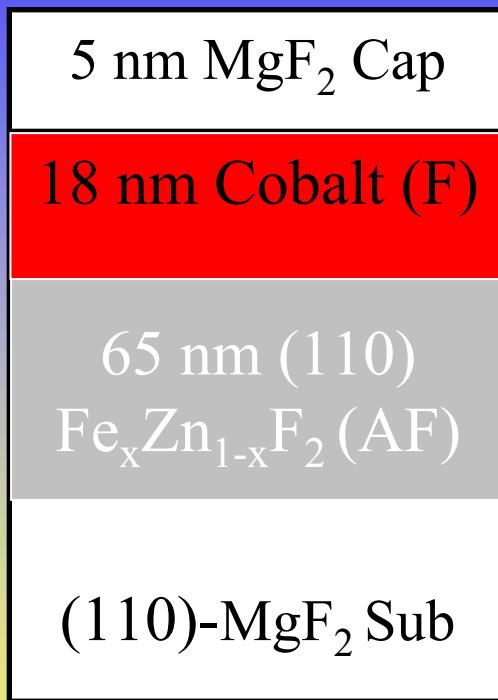
$\text{Co}_{1-x}\text{Mg}_x\text{O}/\text{CoO}$ (0.4 nm) /Co



P. Miltényi, *et al.*, Phys. Rev. Lett., **84**, 4224 (2000)



Sample Profile

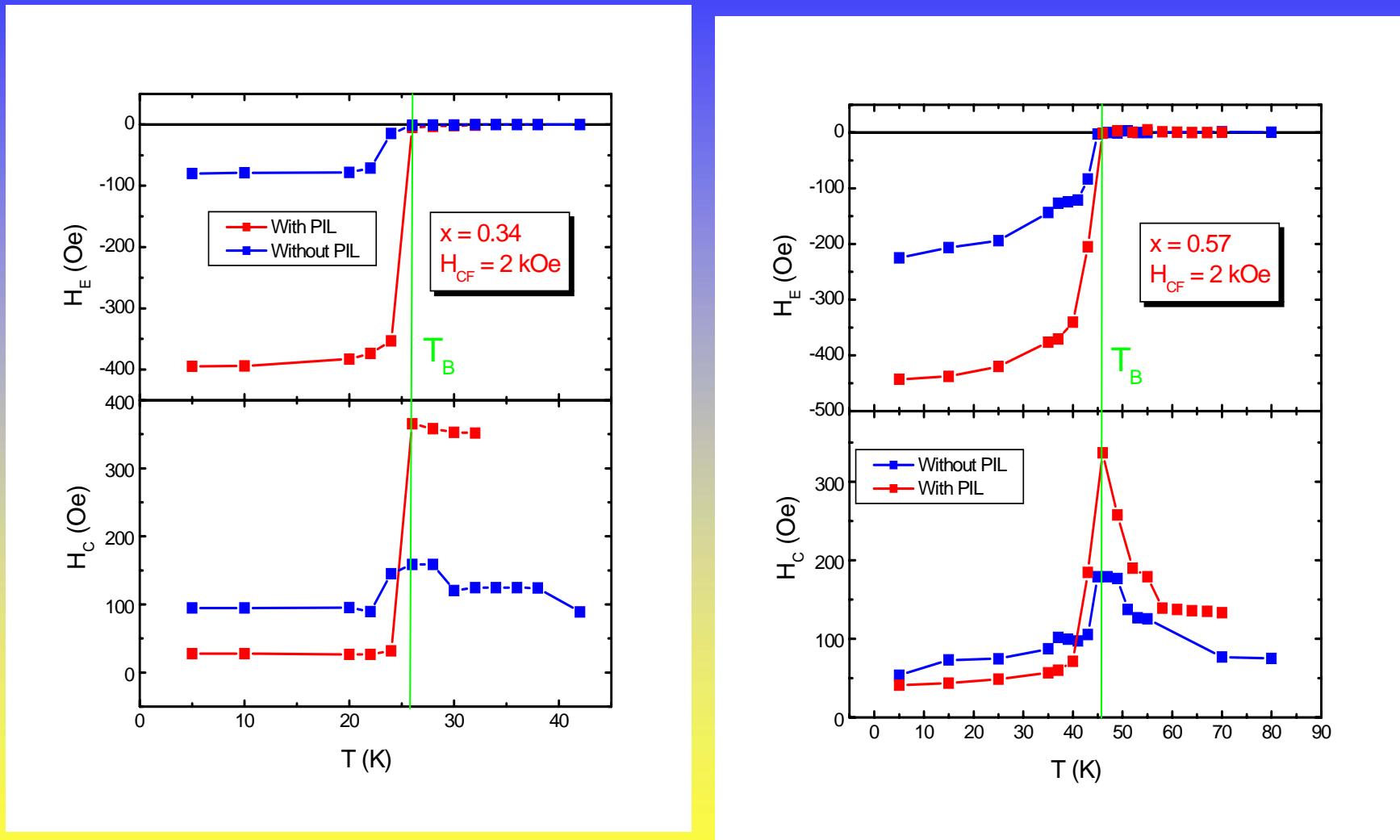


{ Pure interface
layer (PIL)

Magnetic interface changes with x in $\text{Fe}_x\text{Zn}_{1-x}\text{F}_2$



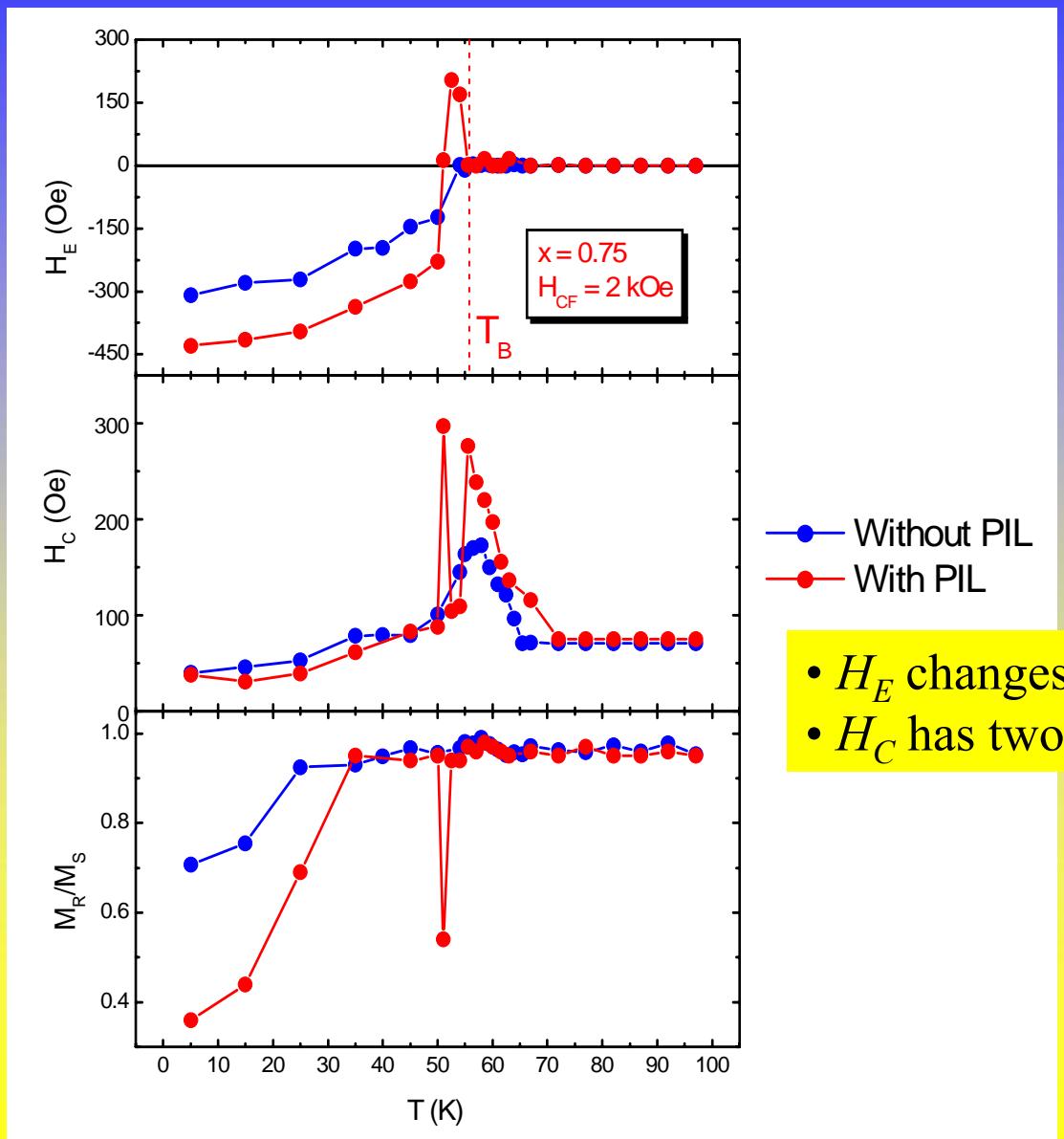
H_E, H_C Dependence on T



PIL affects H_E, H_C ; no effect on T_B

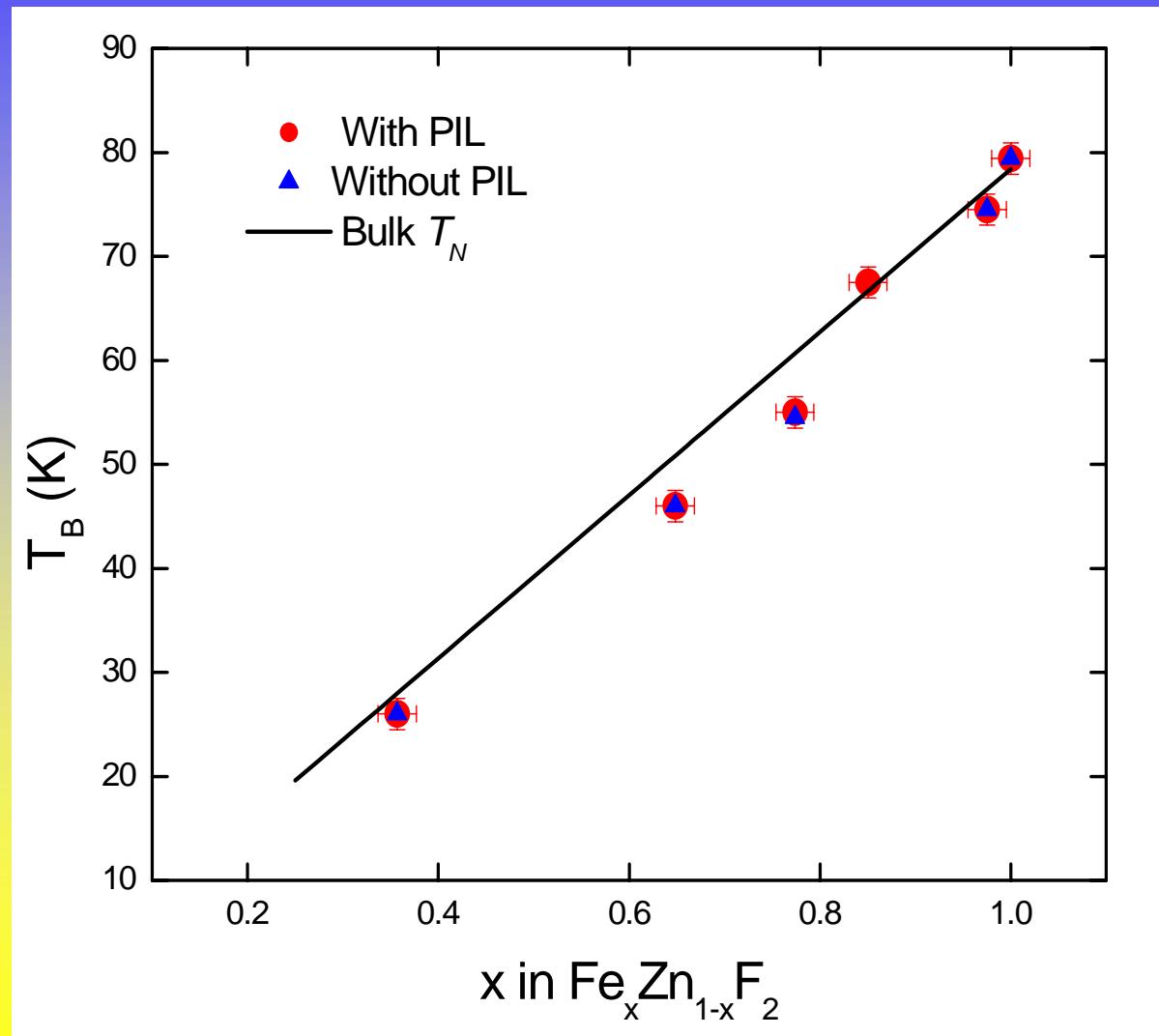


H_E, H_C vs. Temperature for $x = 0.75$





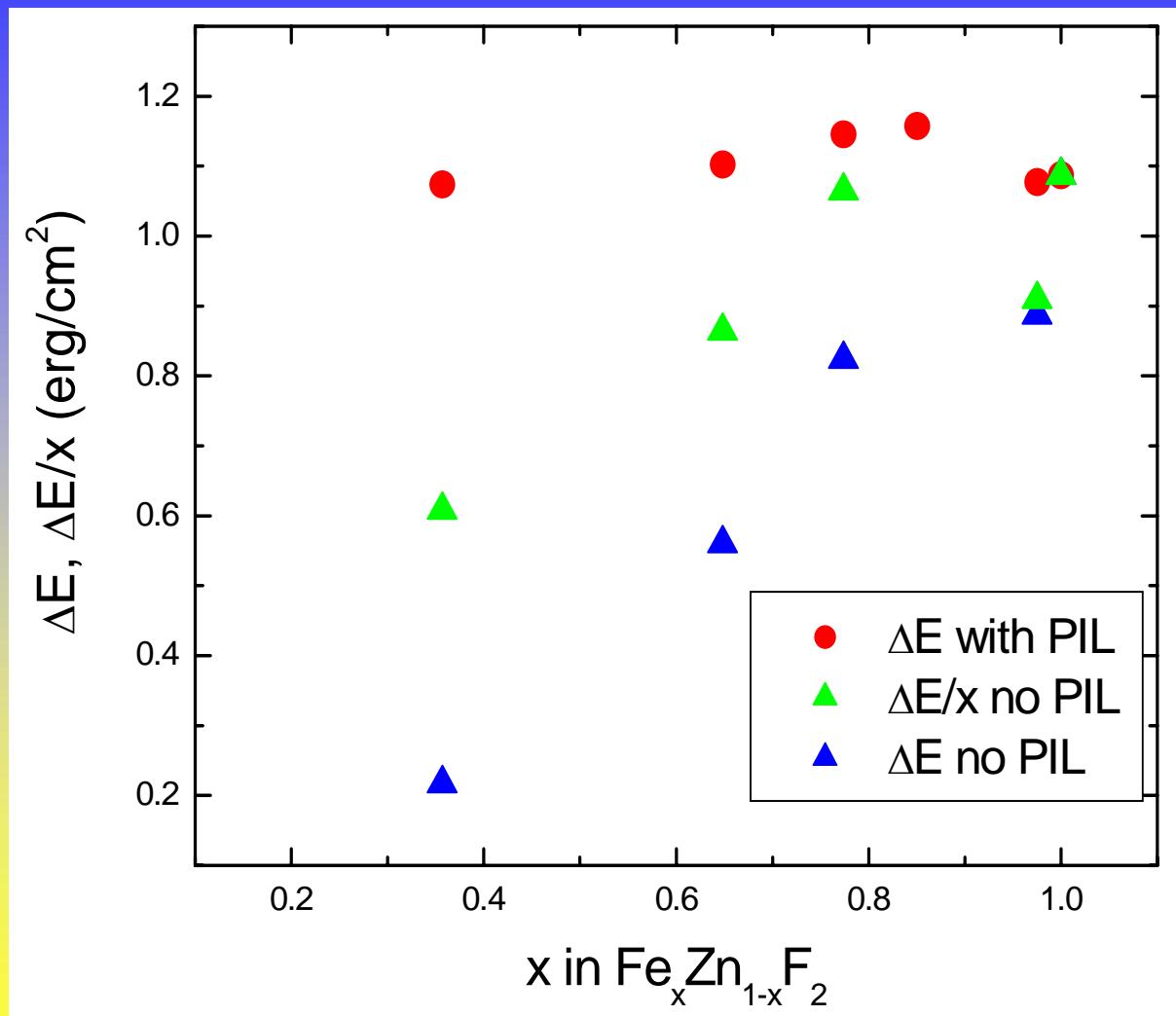
T_B vs. x in $\text{Fe}_x\text{Zn}_{1-x}\text{F}_2$



T_B agrees reasonably well with bulk data



Interface Energy Dependence on x



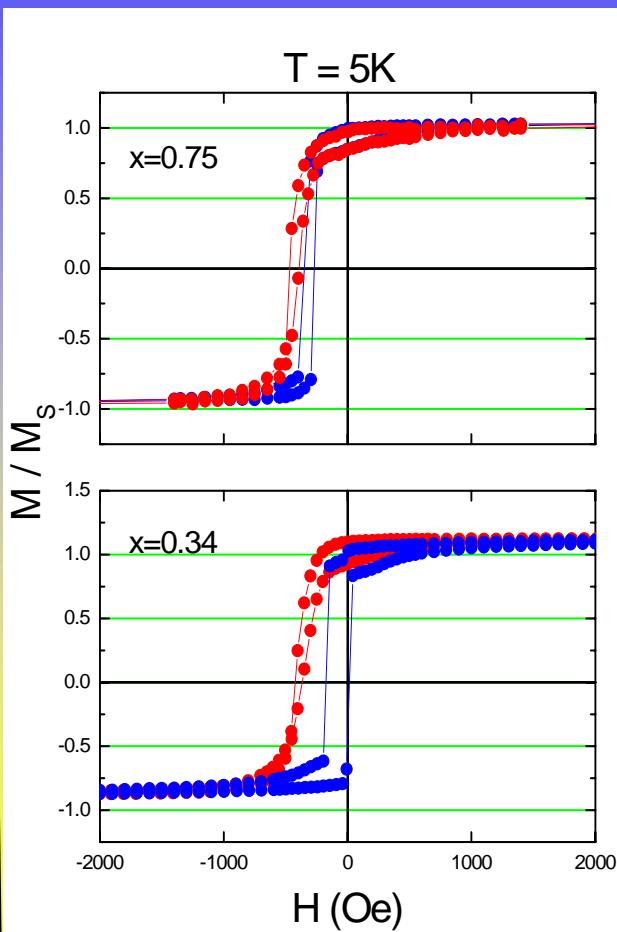
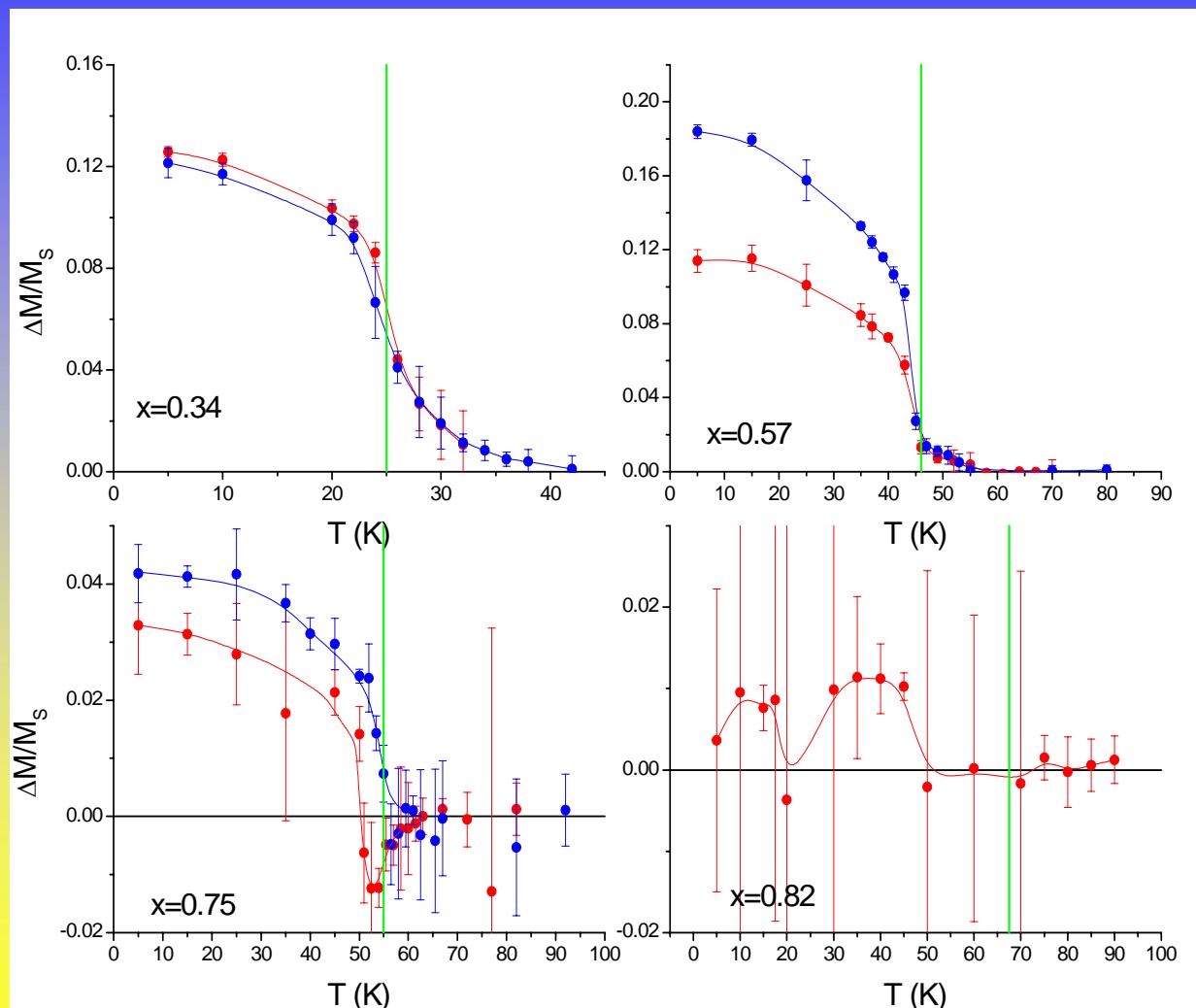
$T = 5\text{K}$

$$\Delta E = -t_{Co} * H_E * M_S$$

- No large H_E enhancement observed

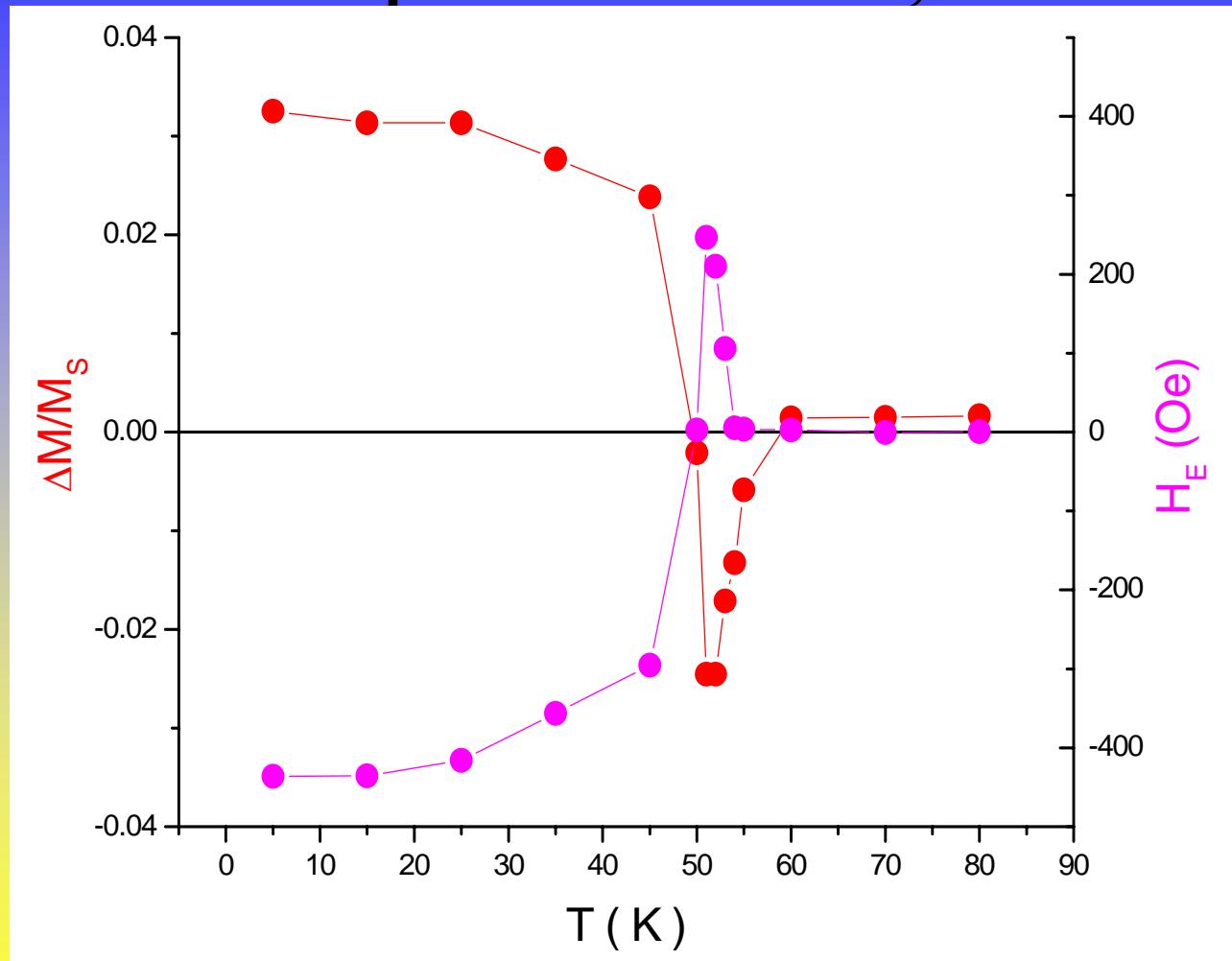


Net AF Magnetization





Uncompensated M, x=0.75



Sign change of H_E due to reversal of AF structure

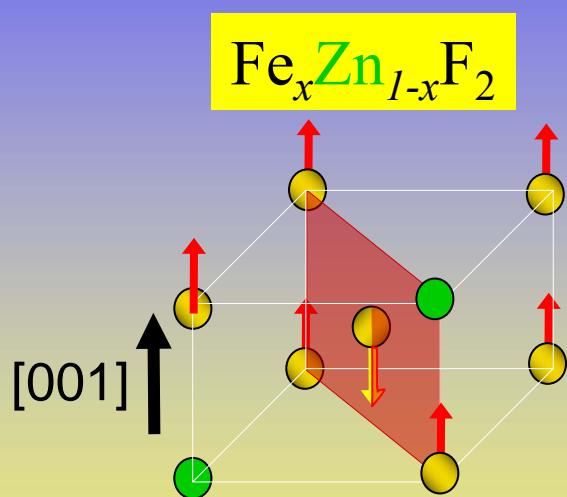


Key Questions

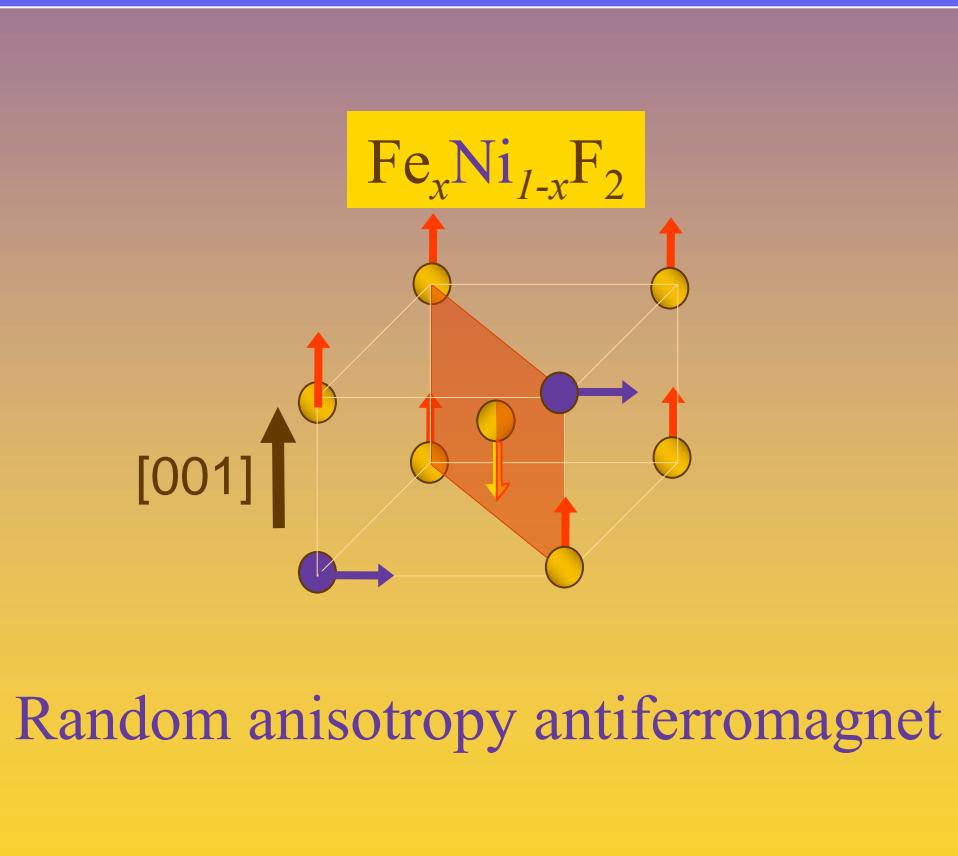
- Can uncompensated moments in the AF be detected?
 - Uncompensated moments exist in AF, not due to “metallization”
 - Can exist up to RT, well above T_N
- Can the effects of uncompensated moments in the AF be studied systematically?
 - Uncompensated M does not necessarily lead to H_E enhancement; critical concentration of impurities must be achieved?
- Can the magnetic anisotropy be studied systematically?



Systems



Dilute antiferromagnet



Random anisotropy antiferromagnet

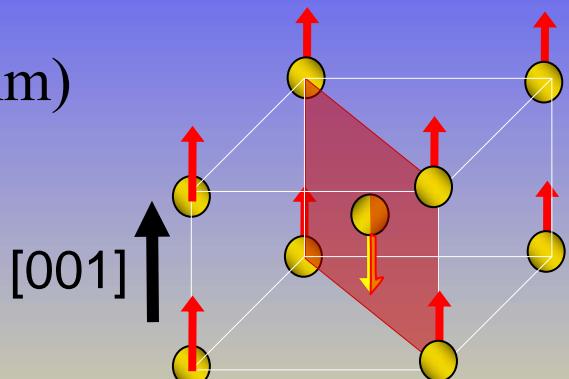
Systematic study of AF anisotropy



Magnetic Order

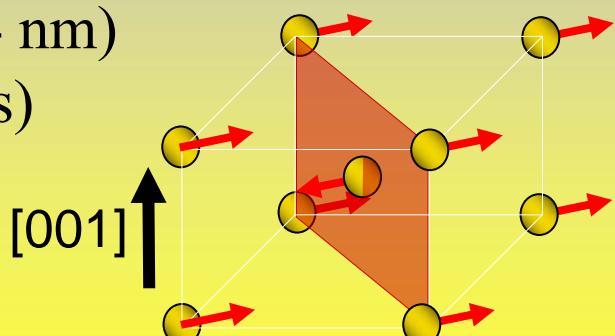
FeF_2

- Rutile structure ($a = 0.4704 \text{ nm}$, $c = 0.3306 \text{ nm}$)
- Antiferromagnetic, $T_N = 78 \text{ K}$
- Magnetization along the c-axis



NiF_2

- Rutile structure ($a = 0.4651 \text{ nm}$, $c = 0.3084 \text{ nm}$)
- Antiferromagnetic, $T_N = 73 \text{ K}$ (80 K in films)
- Weak ferromagnetic
- Magnetization lies in the a-b plane



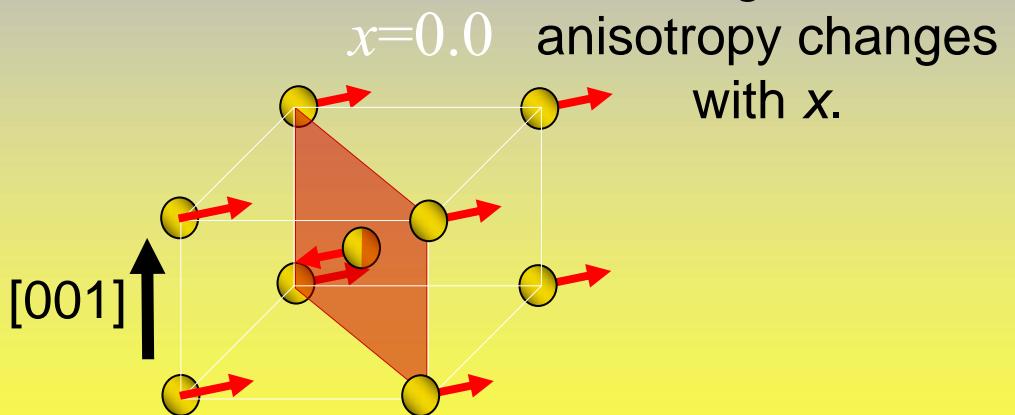
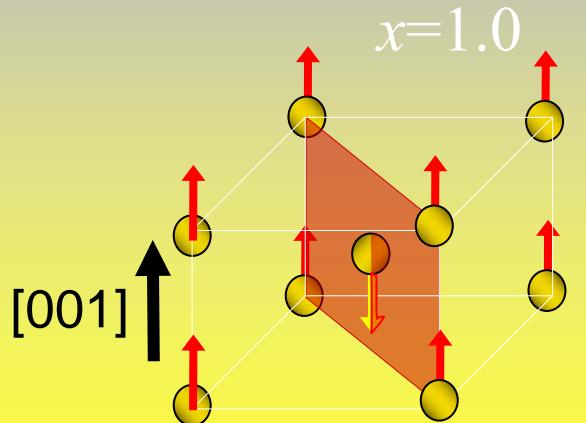


Growth and measurements

MBE Growth

- MgF₂ (110) substrate
- Growth temperature 210 °C
- Fe concentration: 0.0, 0.05, 0.21, 0.49, 0.55 1.0

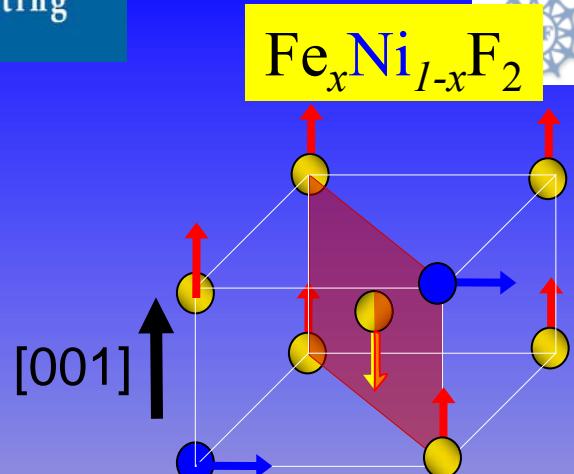
5 nm Al,Pd cap
18 nm Co
50 nm Fe _x Ni _(1-x) F ₂
MgF ₂ (110) sub.





Expectations

For nearest neighbor interactions

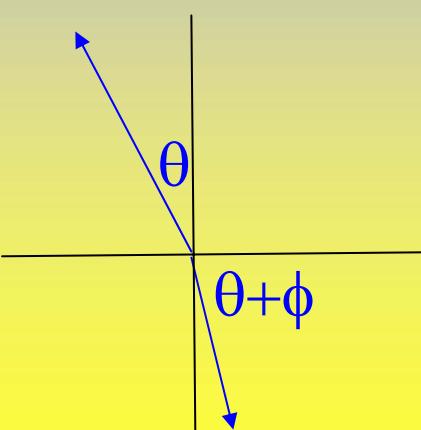


$$\begin{aligned} E = & J_{FeFe} zx^2 S_{Fe}^2 \cos \phi + J_{NiNi} z(1-x)^2 S_{Ni}^2 \cos \phi + J_{FeNi} zx(1-x) S_{Ni} S_{Fe} \cos \phi \\ & + D_{Fe} x S_{Fe}^2 \cos^2 \theta + D_{Ni} (1-x) S_{Ni}^2 \cos^2(\theta + \phi) \end{aligned}$$

For small ϕ , there is a critical Fe concentration x_c beyond which spins will lie along the c-axis:

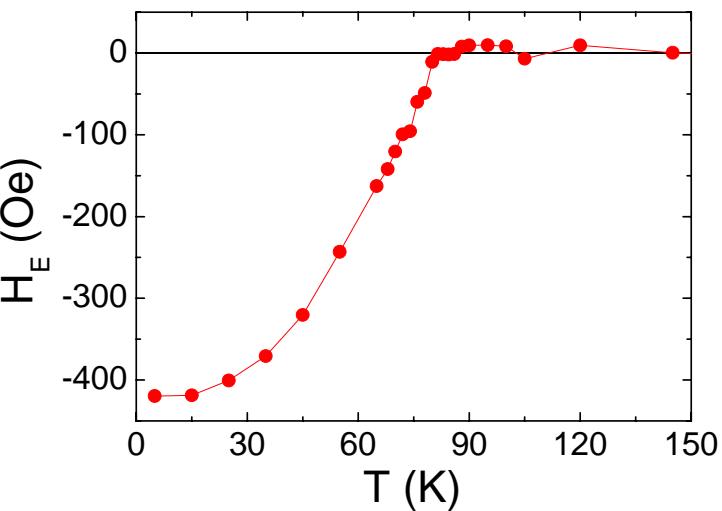
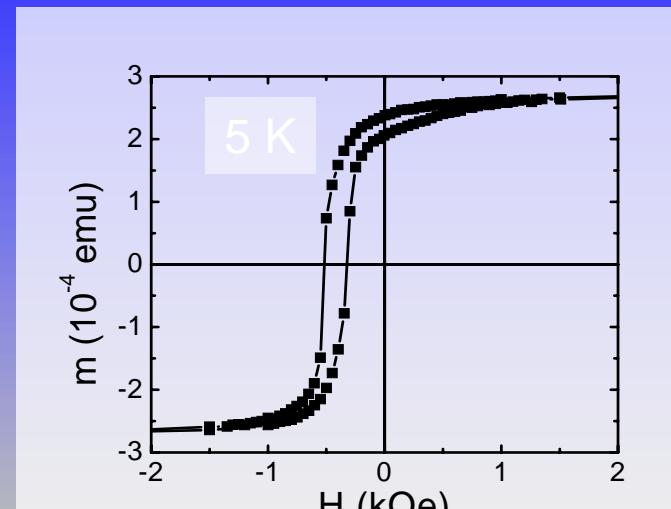
$$x_c = \frac{D_{Ni} S_{Ni}^2}{D_{Ni} S_{Ni}^2 - D_{Fe} S_{Fe}^2}$$

For FeF₂ and NiF₂ $x_c = 0.14$



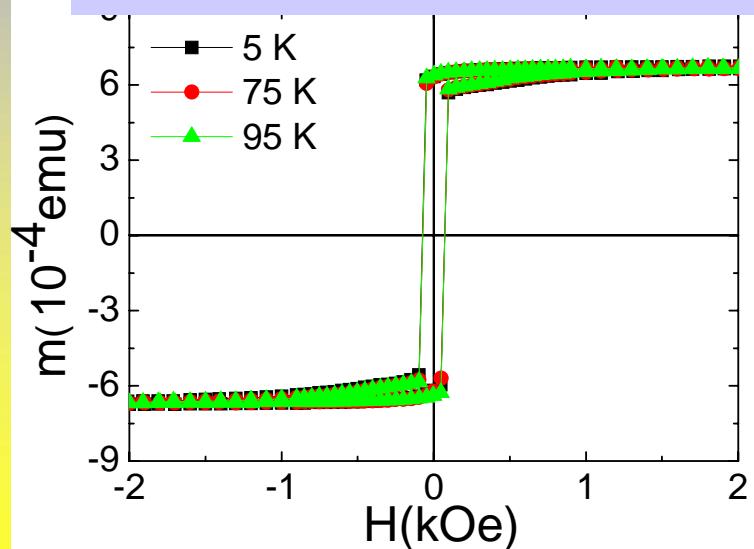
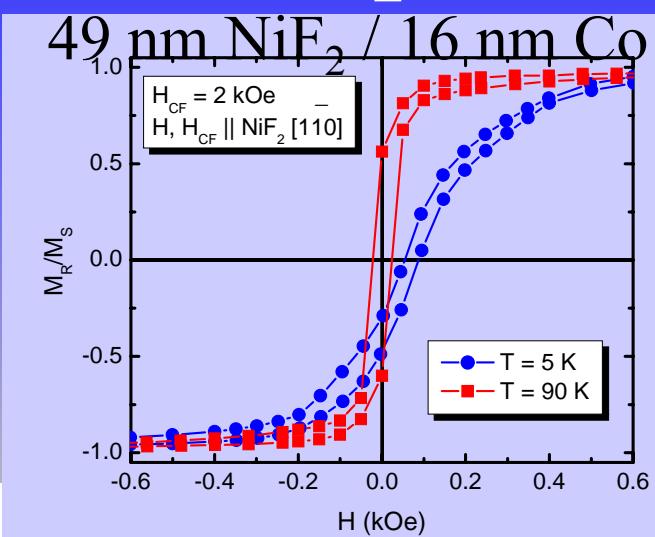


FeF₂/Co



- Exchange bias along c-axis
- $T_B \sim 81 \text{ K}$

NiF₂/Co



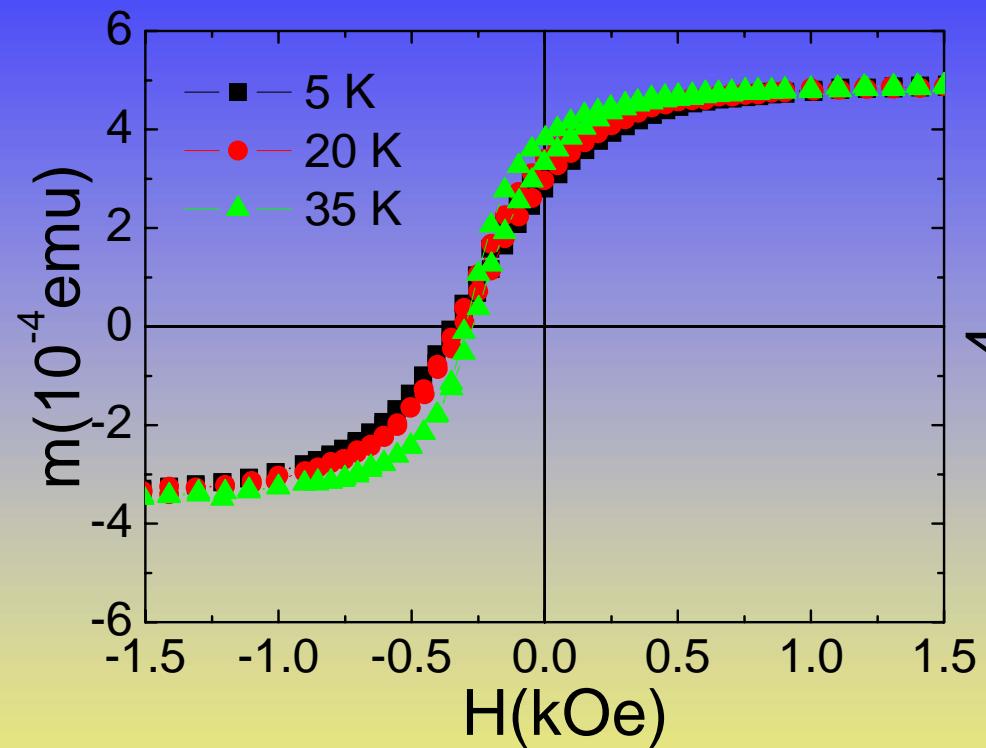
- No exchange bias along c-axis

$H \perp c$

$H \parallel c$

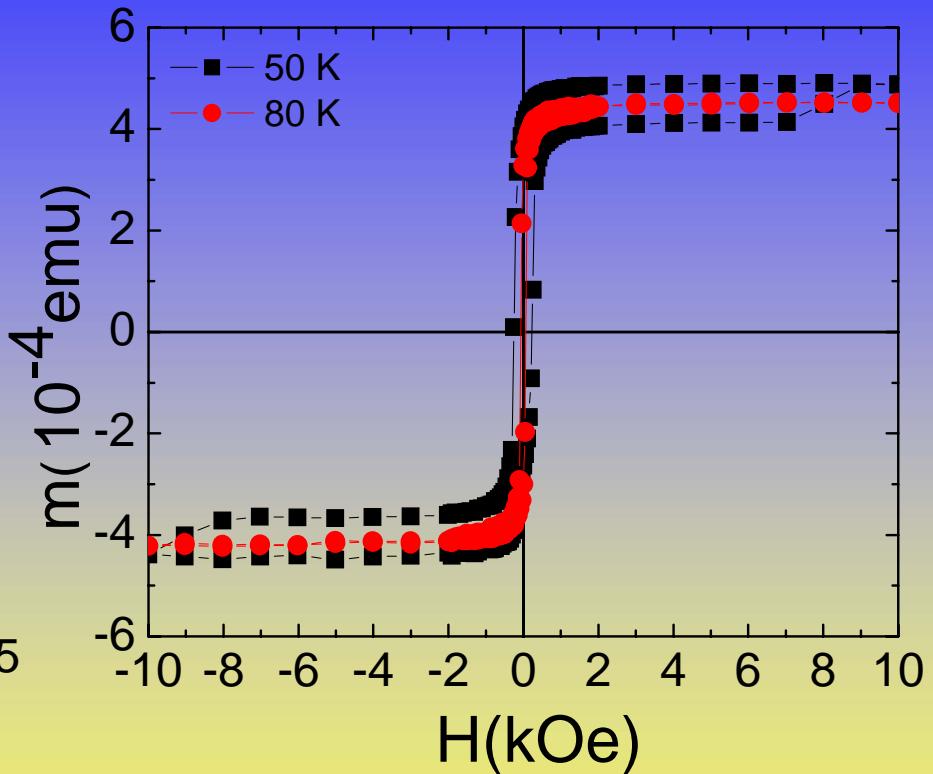


$\text{Fe}_{0.05}\text{Ni}_{0.95}\text{F}_2/\text{Co}$



For $T \leq 45 \text{ K}$

- Negative exchange bias effect along the c-axis
- Asymmetric saturation magnetization



For $50 \text{ K} \leq T \leq 70 \text{ K}$

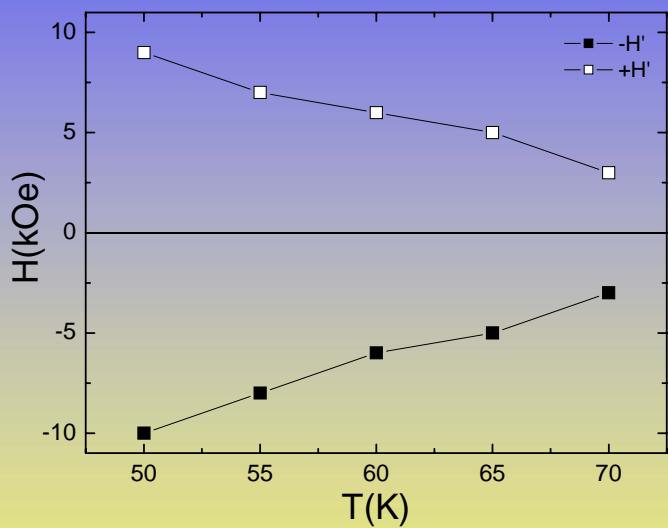
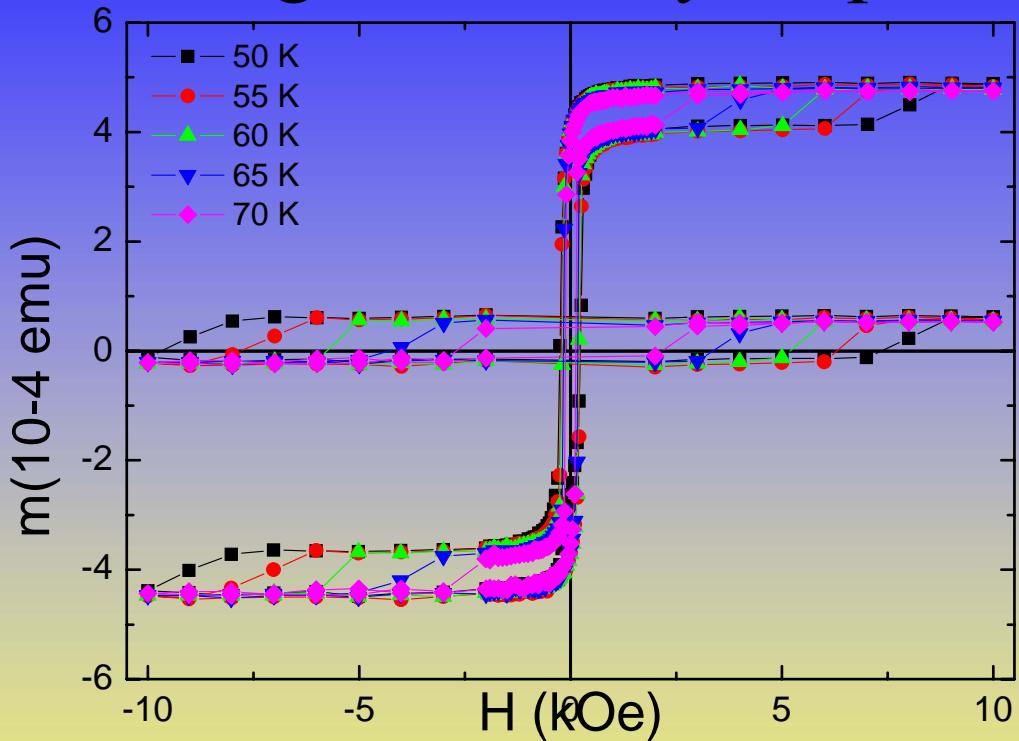
- No exchange bias effect
- Big hysteresis loop

For $75 \text{ K} \leq T$

- No exchange bias effect



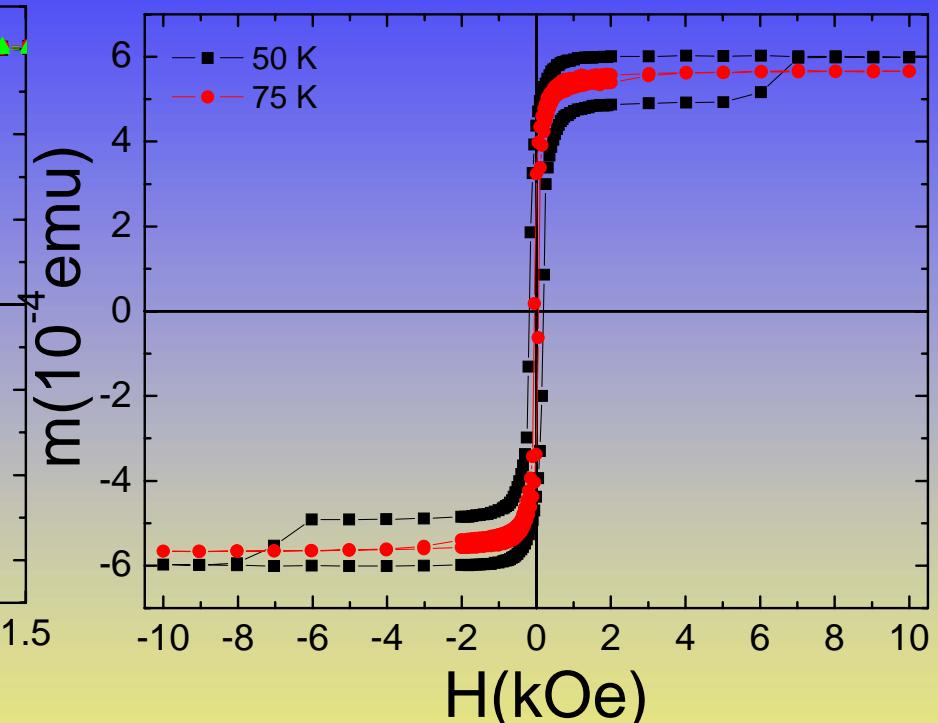
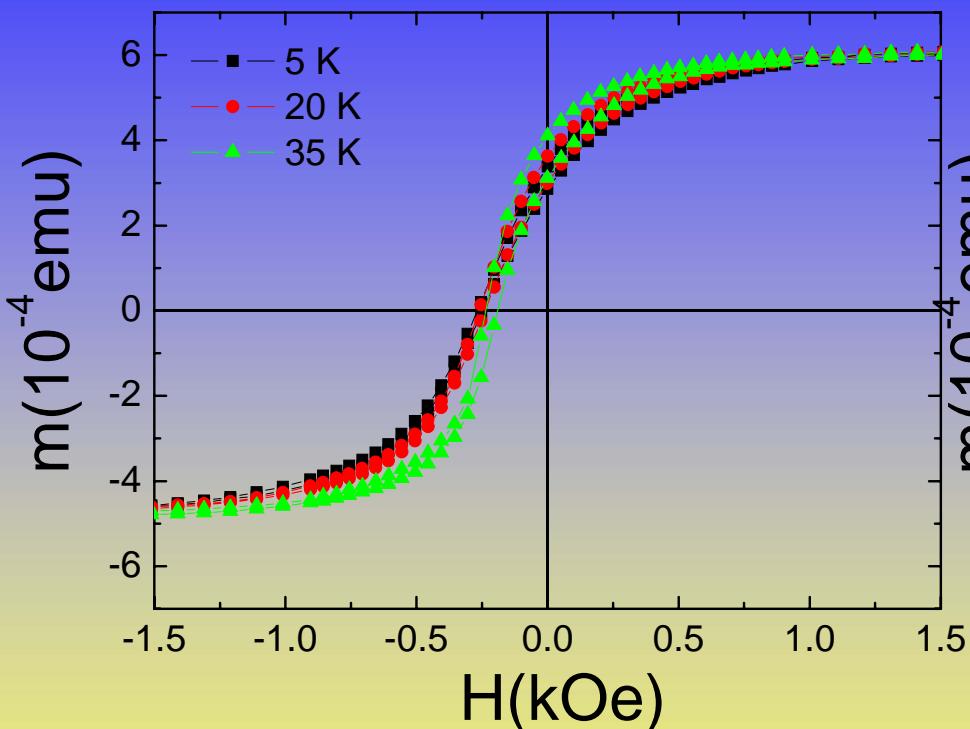
Large coercivity loops of $\text{Fe}_{0.05}\text{Ni}_{0.95}\text{F}_2/\text{Co}$



- For $50 \text{ K} \leq T \leq 70 \text{ K}$, large coercivity loops appear for the scanning field range -10 kOe to 10 kOe.
- Negative exchange bias effect ($H_E \sim -500 \text{ Oe}$) for $T = 50 \text{ K}$ and 55 K



$\text{Fe}_{0.21}\text{Ni}_{0.79}\text{F}_2/\text{Co}$

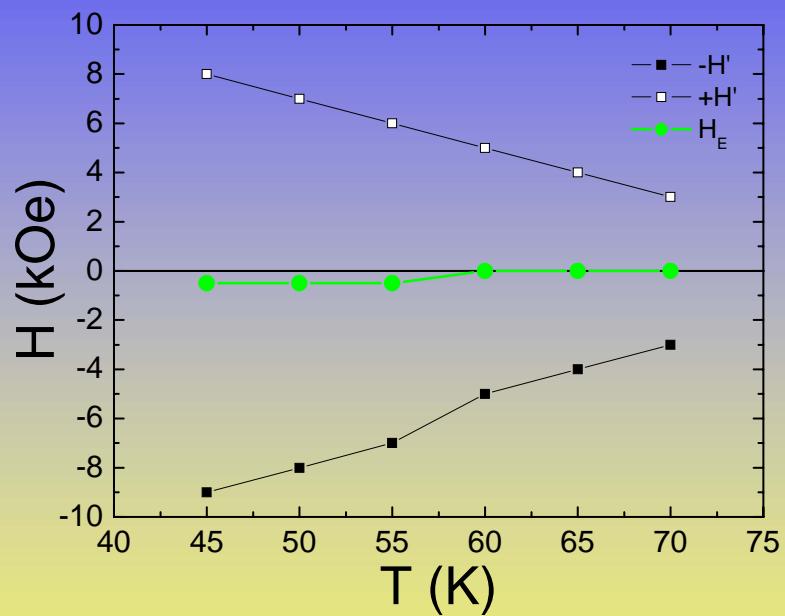
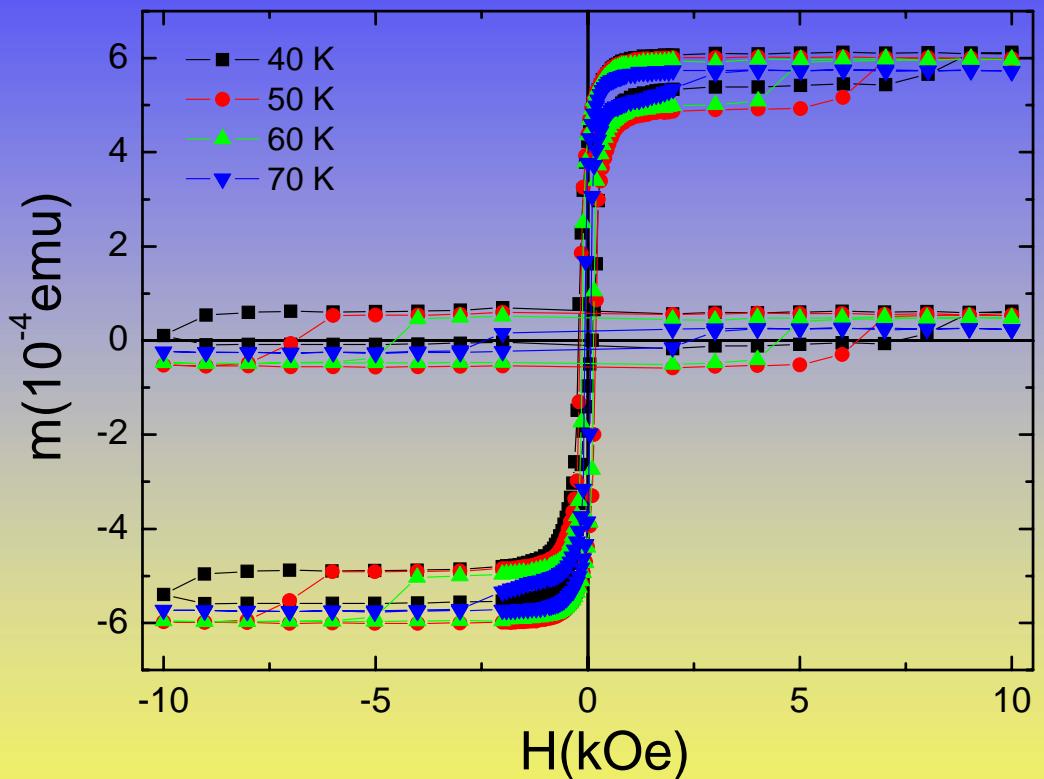


- Similar behavior to $\text{Fe}_{0.05}\text{Ni}_{0.95}\text{F}_2/\text{Co}$
- Negative H_E along the c-axis at $T \leq 40$ K
- Asymmetric saturation magnetization

- For $45 \text{ K} \leq T \leq 70 \text{ K}$
- No exchange bias effect
 - Fat hysteresis loop
- For $75 \text{ K} \leq T$
- $H_E = 0$



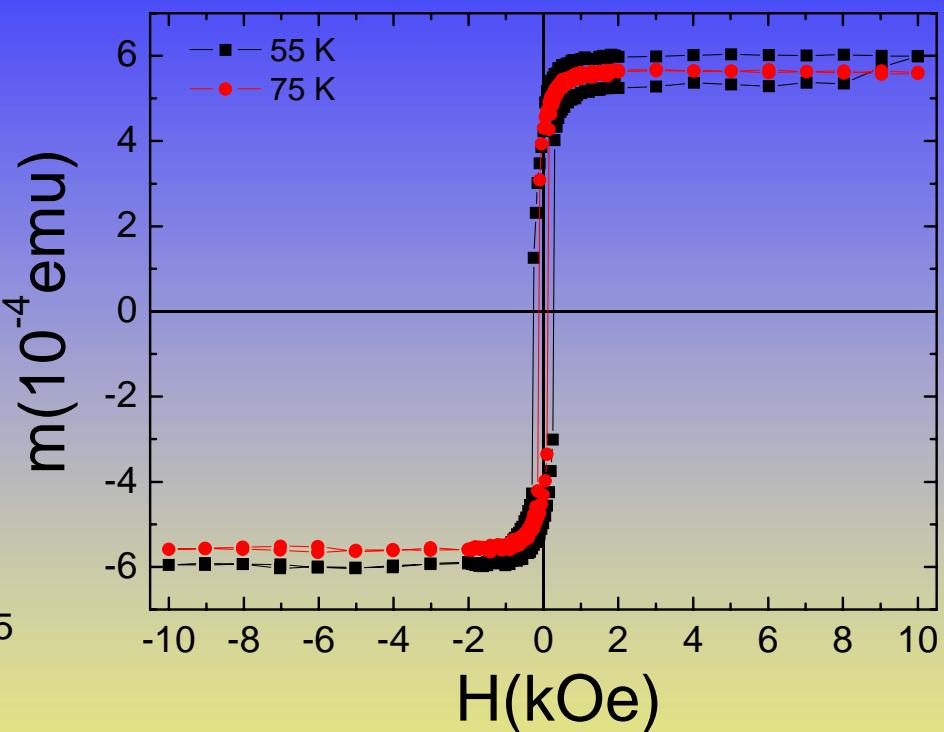
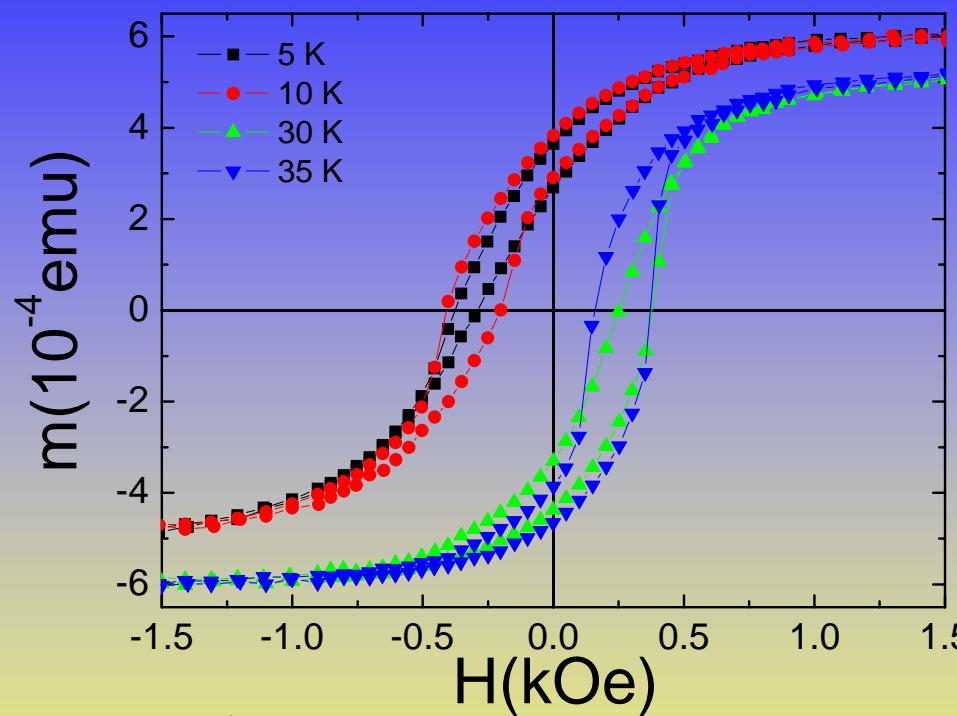
Large H_C loops of $\text{Fe}_{0.21}\text{Ni}_{0.49}\text{F}_2/\text{Co}$



- For $40 \text{ K} \leq T \leq 70 \text{ K}$, large H_C loops appear for the scanning field range $\pm 10 \text{ kOe}$
- Negative exchange bias effect ($H_E \sim -1000 \text{ Oe}$) for $40 \text{ K} \leq T \leq 55 \text{ K}$



Fe_{0.49}Ni_{0.51}F₂/Co

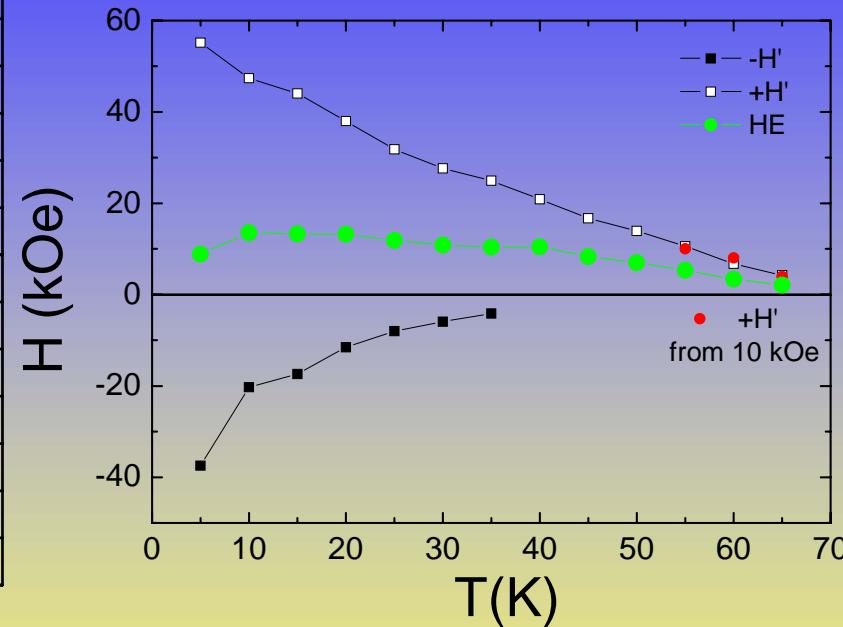
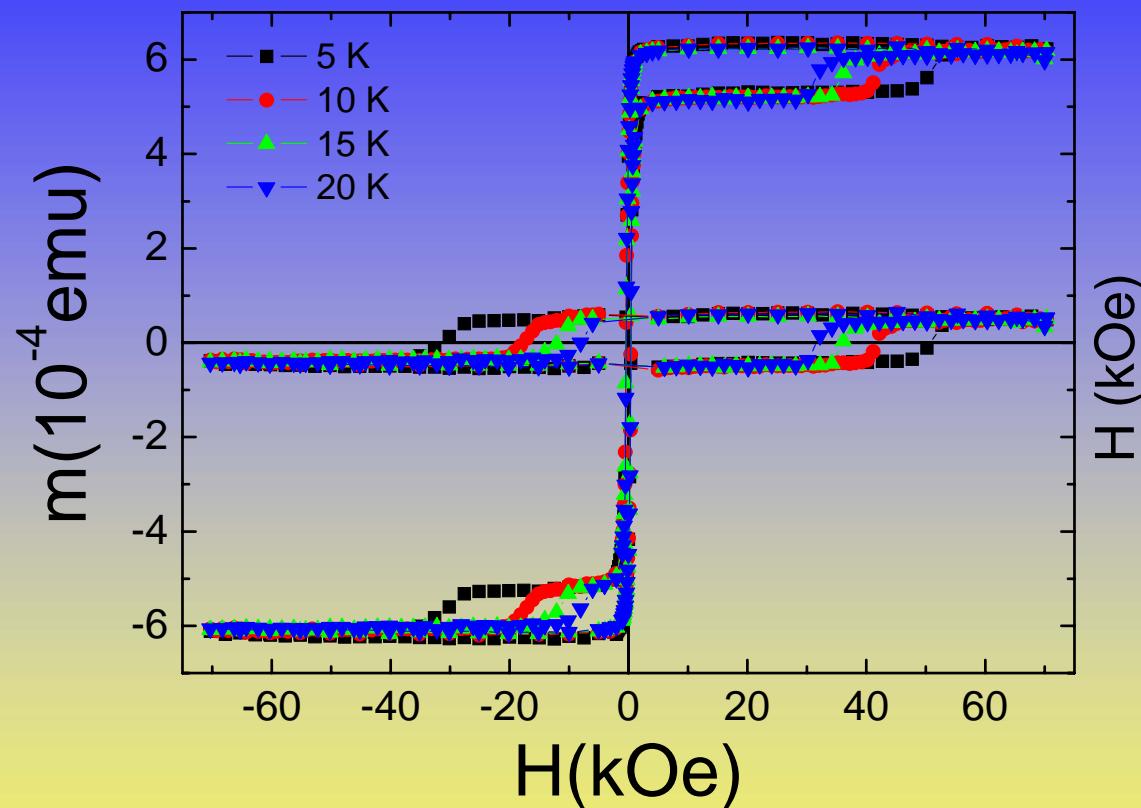


- For $25 \text{ K} \leq T \leq 50 \text{ K}$
- Positive exchange bias effect
 - Asymmetric saturation magnetization

- For $70 \text{ K} \leq T$
- No exchange bias effect



Large H_C loops of $\text{Fe}_{0.49}\text{Ni}_{0.51}\text{F}_2/\text{Co}$

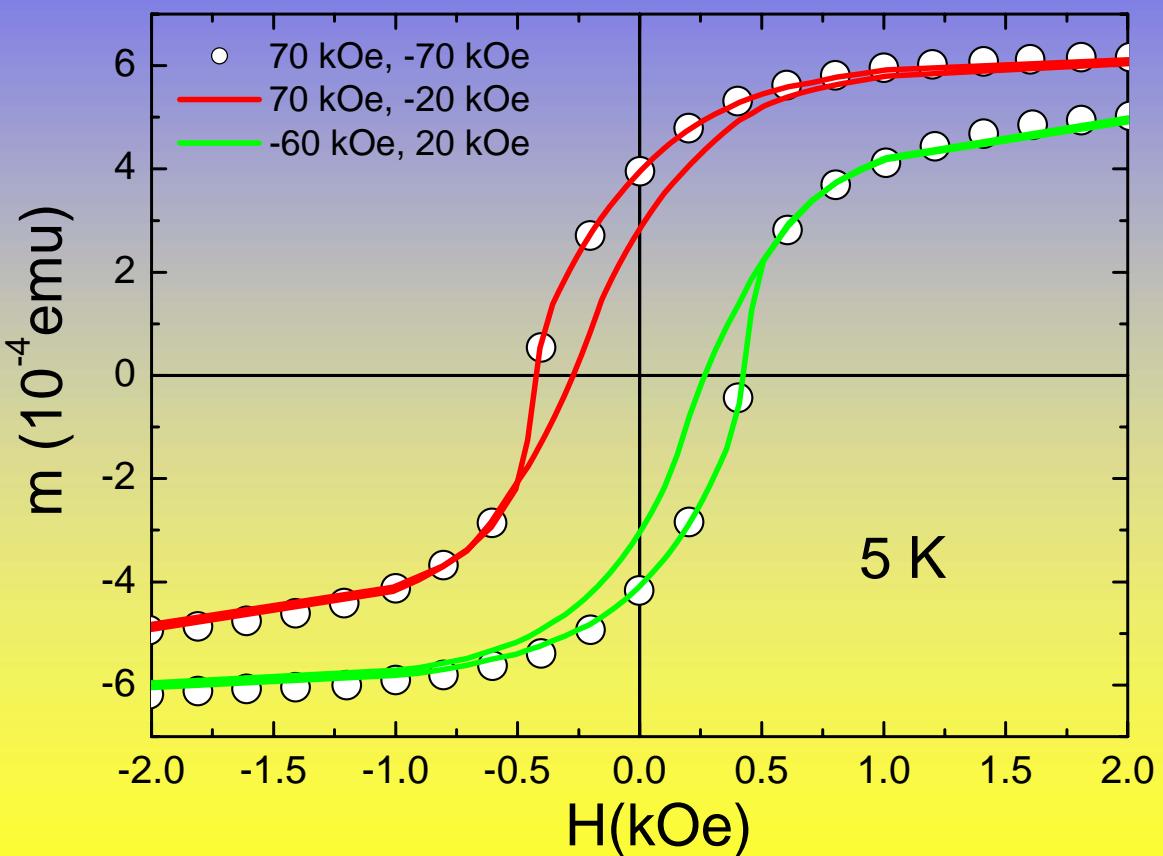


- For $5 \text{ K} \leq T \leq 55 \text{ K}$, large H_C loops appear for $H = \pm 70 \text{ kOe}$
- Positive exchange bias effect with $H_E \geq 10 \text{ kOe}$
- For $55 \text{ K} \leq T \leq 70 \text{ K}$, large H_C loops appear for $H = \pm 10 \text{ kOe}$



Fe_{0.49}Ni_{0.51}F₂/Co

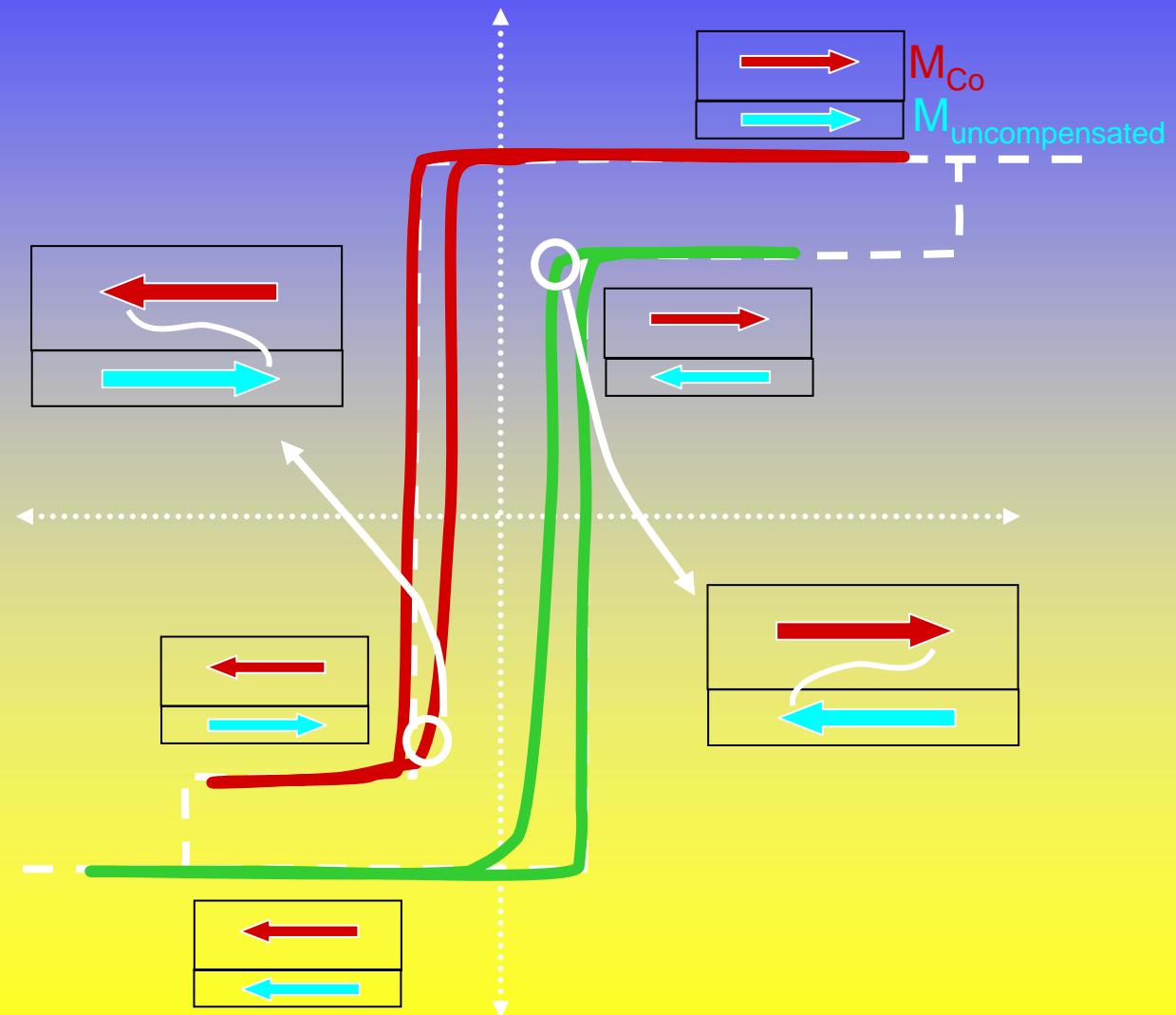
- Tunable exchange bias (reversal of fat hysteresis)





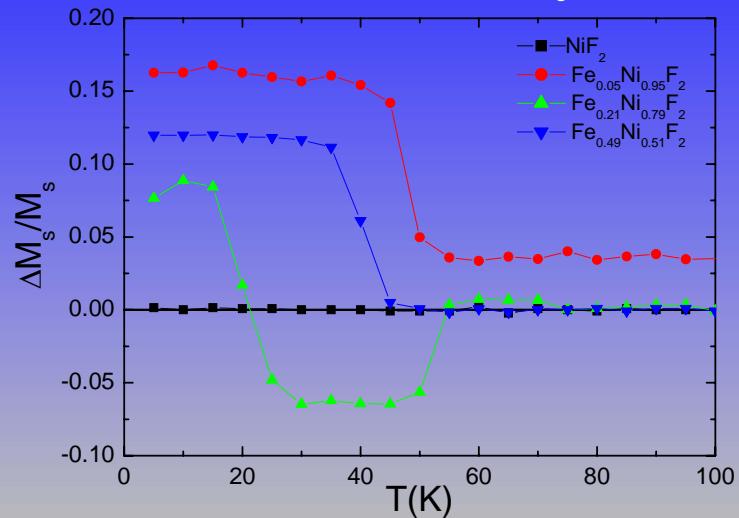
Negative and positive exchange bias

- M_{Co} favors **parallel** exchange coupling with $M_{\text{uncompensated}}$

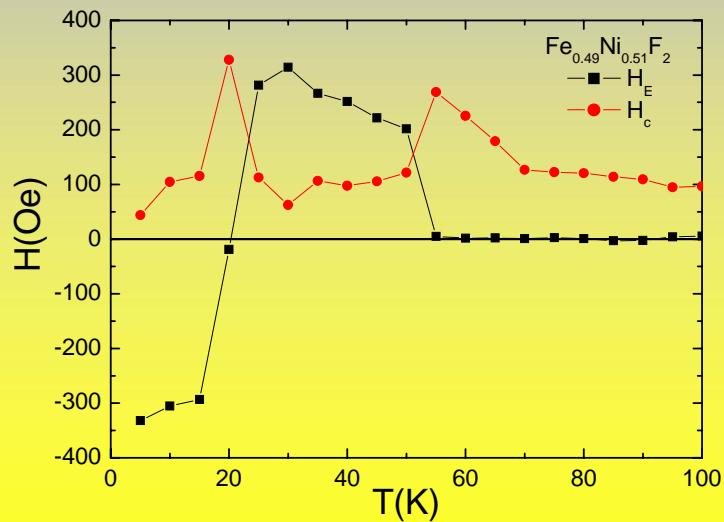




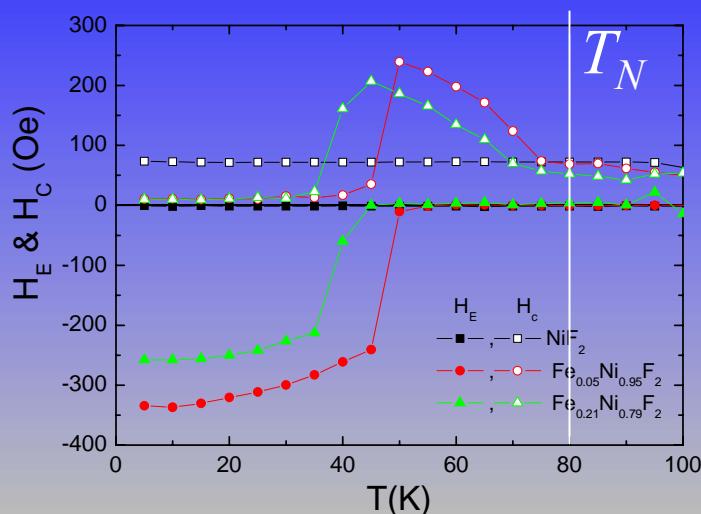
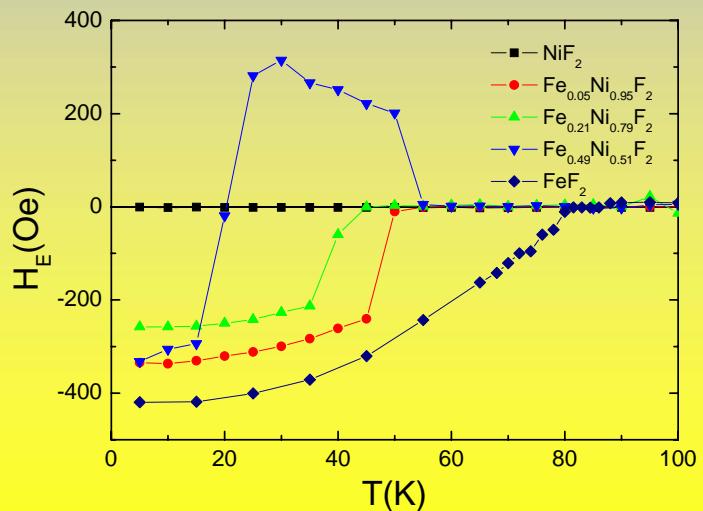
Summary for $\text{Fe}_x\text{Ni}_{(1-x)}\text{F}_2/\text{Co}$ bilayers



Uncompensated magnetization



Exchange bias and coercive field

Exchange bias and coercive field
(note low T_B)

Exchange bias field



Key Questions

- Can uncompensated moments in the AF be detected?
 - Uncompensated moments exist in AF, not due to “metallization”
 - Can exist up to RT, well above T_N
- Can the effects of uncompensated moments in the AF be studied systematically?
 - Uncompensated M does not necessarily lead to H_E enhancement; critical concentration of impurities must be achieved?
- Can the magnetic anisotropy be studied systematically?
 - Low magnetic anisotropy leads to reversible H_E , in addition to low T_B
 - Reversible H_E also required uncompensated M in the AF